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   Johnston, C. M. (1953) *Brit. J. Industr. Med.* **10**, 41.
   B.S. 2980 (1958) *British Standard for Pure Tone Audiometers*. British Standards Institution, London.
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FOREWORD TO VOLUME 1

by

The President of the British Occupational Hygiene Society

FOREWORD

THE founding of the *Annals of Occupational Hygiene* marks an important step by the British Occupational Hygiene Society in pursuance of its object "to promote the science of occupational hygiene". The journal will meet a long-felt need by bringing together, in a single publication, papers from the various fields of science, engineering and medicine which contribute to the common cause of safeguarding the health of the industrial worker. It will form a natural supplement to the Society's Conferences and Scientific Meetings. These various activities and, indeed, the formation of the Society itself, are indicative of the growth of occupational hygiene as a distinct profession. Publication of the *Annals* has been widely welcomed at home and overseas. The Society is grateful to those distinguished men who have demonstrated their support in a practical way by consenting to serve as Overseas Editors.

It is the intention of the Editorial Committee that the *Annals* shall predominantly comprise original articles of a high standard concerned with occupational hygiene and the underlying sciences. A balance will be maintained between the various branches of the subject, not more than 25 per cent of the contributions being of a purely medical character. A limited amount of space will be devoted to reviews and to the Society's news.

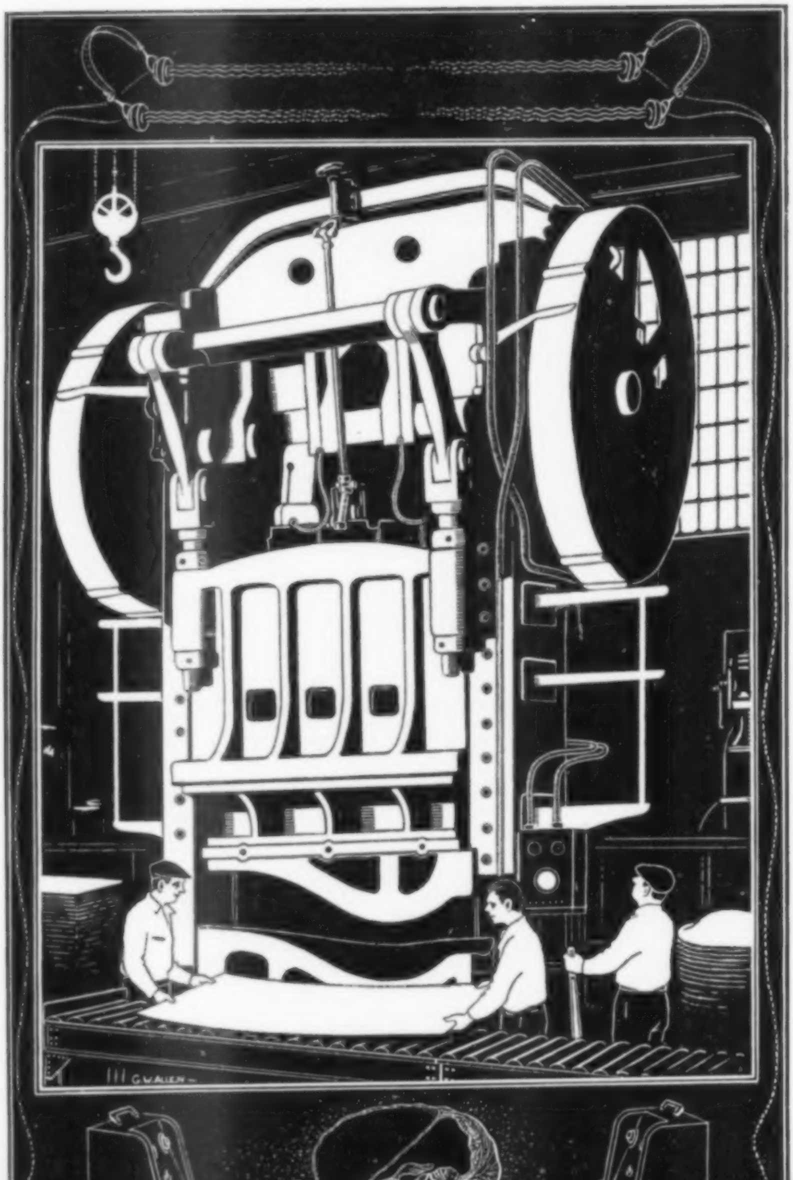
Although some of the published material will consist of papers presented at the Society's Conferences and Scientific Meetings, other contributions will be welcomed and will be acceptable in languages other than English, in keeping with the international character of the publication. For the first Volume some issues have been devoted to a single theme, others have been more general. It is not thought desirable at this early stage to adopt a rigid format but rather to preserve flexibility; the Editor will welcome comments.

W. H. Walton

National Coal Board,
Mining Research Establishment,
Isleworth,
Middlesex.

MR. W. H. WALTON

President of the British Occupational Hygiene Society, 1959–60



NOISE IN INDUSTRY

Ann. Occup. Hyg. Vol. 1, pp. 1-10. Pergamon Press, London, 1958. Printed in Great Britain.

THE CLINICAL AND PHYSIOLOGICAL EFFECT OF NOISE

TERENCE CAWTHORNE

London

UNACCUSTOMED noise so often prompts the remark: "This noise is quite deafening". This is a figure of speech because those who use it are confident that when the noise subsides their hearing will return. Indeed it usually does so. But those whose work exposes them to too much sound, too often, and for too long will in time find out that this figure of speech has become reality.

The harmful effect of prolonged exposure to noise while at work has been the subject of occasional comment for more than a century, the first observation being made by FOSBROOKE (1830) upon deafness in blacksmiths. To the noise of metal beating upon metal there has in the course of industrial progress been added the noise of machinery, the noise of engines, and finally, noisiest of all, the sound of air compressors and jet engines. This spread of noise into so many industrial processes combined with new methods of detecting early hearing loss by means of pure tone and speech audiometry has focused attention upon the danger to hearing of prolonged exposure to very loud sound. Much has been written on the subject in recent years and legislation has been introduced in certain countries and states.

Nevertheless general opinion still regards noise as an annoying distraction rather than a danger to hearing; though it has been shown that working in an atmosphere of regular noise, even when the overall level is as high as 110 phons, has little or no effect upon work output or upon general health, even though all the time it is slowly and, until a certain level is reached, imperceptibly causing irreversible damage to the end organ of hearing. Once noise reaches a level at which it begins to be felt (120 phons) or even to hurt (130 phons), then of course it becomes intolerable; a state of affairs which can be caused by jet engine noise.

However, before going any further into the effect of noise upon hearing it will be as well to inquire into the sense of hearing and the organ which serves it.

Hearing is the latest addition to the battery of senses with which man and most air-breathing animals are endowed. It is latest in the evolutionary sense because fish do not have an auditory apparatus as they have no need for a receptor apparatus capable of responding to airborne sound waves. It is probable that they are able to appreciate certain waterborne sounds with the saccule, which is part of the intricate balancing organ. From this has gradually evolved the end organ of hearing which reaches its full state of development in mammals. This is why hearing and balance are so intimately connected and in consequence disorders of hearing are sometimes associated with disturbed balance.

At first sight it would seem that the prime object of the sense of hearing is to hear speech, and while in man this may be its most important function this certainly does not apply to animals, in whom the sense of hearing, as well as all the other senses, is devoted to preservation of self and preservation of the species. The warning note of the startled blackbird, the owl which on the blackest night can

pinpoint its prey by ear, and the crowing of the barnyard fowl are instances of the way in which hearing in animals is used to evade danger, find food, and encourage a mate. The sound which "makes you jump out of your skin" is an example of the primitive purpose of hearing which survives in man. The cries, grunts and squeals with which our ancestors expressed their feelings have gradually become organized into speech and language which enable our thoughts and ideas, as well as our instincts and emotions, to be exchanged and remembered.

Thus hearing, and through hearing, speech and language, have played a large part in enabling man to raise himself above the rest of the animal kingdom. The evolutionary background to the sense of hearing has been mentioned at this stage in order to draw attention to some of the instinctive and subconscious reactions which may be modified by deafness.

Though modern man does not need his hearing for the instinctive purposes for which it was first evolved, it does play a very large part in his everyday life. For man after all is a social animal. He likes to talk and occasionally he is prepared to listen. If his hearing fails it is tiring for him to try and keep his place in the social circle, and tiresome for those who have to make the special effort necessary to keep him there.

Anyone with a deaf relative or friend knows how difficult it can be to keep them in a general conversation. How many times it has been said of the hard of hearing that they can hear when they want to. There is of course a half-truth in this. To hear all that is being said in a general conversation places a great strain on the hard-of-hearing person, and in consequence when the conversation does not seem to be directly concerning him, he so to speak sits back for a rest, stops listening and lets the sounds flow by without paying too much attention. If directly addressed or he catches a word which concerns him, he will strain to hear again. Having an invisible infirmity, the hard-of-hearing person appears to be quite normal so that those who try to converse with him have little incentive to sustain the special effort of slow and careful enunciation which is needed to make them audible. To do so is a nuisance and the hard of hearing are often very conscious of this and, according to their temperament, they are sorry to be such a nuisance or they resent the apparent lack of sympathy.

It is often said that the deaf are inclined to be suspicious that others are talking about them or laughing at them, but this is rarely the case. It will nearly always be found that lack of consideration for their infirmity is the basis for any ill feelings they may have.

Having considered the effect of deafness upon the individual, it will now be convenient to inquire into the mechanical processes involved in hearing so as to appreciate how hearing can be affected by too much noise.

Airborne sound waves pass down the external ear canal to reach the eardrum, which they set into vibration (Fig. 1). This movement is transmitted through the ossicular chain which connects the eardrum with the oval window leading to the internal ear. The fluid perilymph contained in the internal ear responds to the to and fro movement transmitted to it through the oval window and a fluid wave is set up which travels in the direction of the other window in the bony internal ear, the round window (Fig. 2). This is so placed that the fluid wave passes across the basilar membrane upon which the end organ of hearing, the Organ of Corti, rests

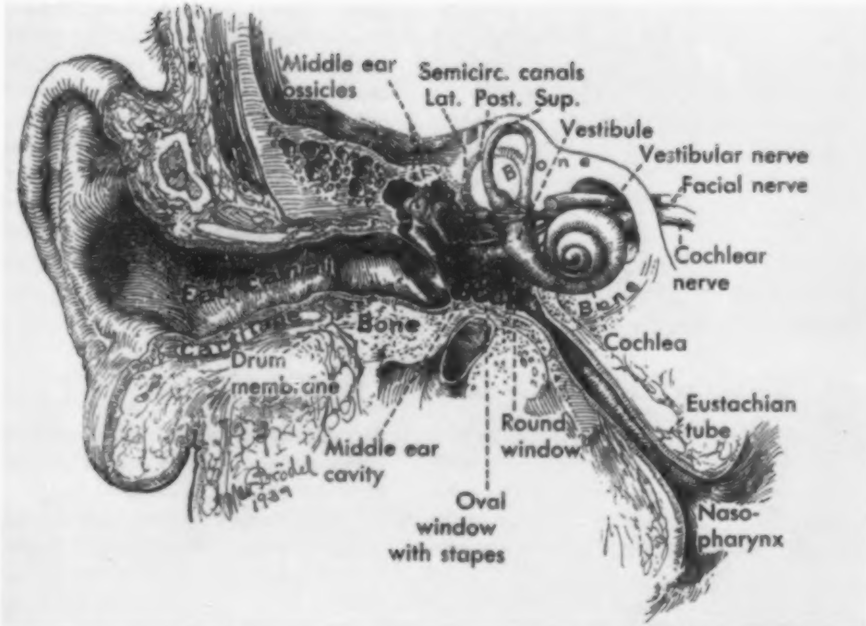


FIG. 1. Diagram of the outer, middle and internal parts of the ear. (From BRÖDEL, M. (1946) *Anatomy of the Human Ear*. Saunders, Philadelphia. By courtesy of W. B. Saunders Co. Ltd.)

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(Fig. 3). The resulting movement presses the hair cells of the Organ of Corti against the covering tectorial membrane and this results in a stimulus being sent up the auditory nerve (Fig. 4). So long as the hair cell mechanism is intact and sound waves can reach it, hearing is possible. If the hair cell mechanism cannot function properly, then hearing is impaired. Now the basilar membrane is so constructed that at the base of the cochlea near the window it is attuned to respond more readily to high-frequency vibrations, while at the apex of the cochlea the fibres of the basilar membrane are long and slack and respond more readily to low-frequency vibrations.

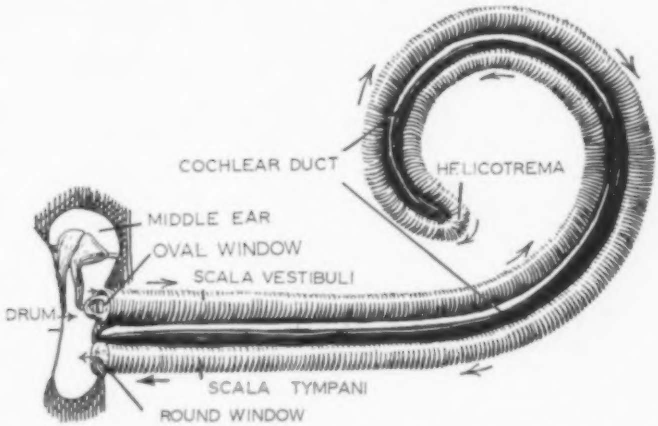

FIG. 2. Diagram of the middle ear and cochlea. The cochlea is represented as partially uncoiled. Sound passes in through the oval window, travelling along the scala vestibule and then back along the scala tympani. At the same time it moves across the cochlear duct which contains the Organ of Corti lying on the basilar membrane. (Reproduced by courtesy of KRIEG, W. J. S. (1953) *Functional Neuroanatomy* (2nd Ed.). Blakiston Div., McGraw-Hill, New York.)

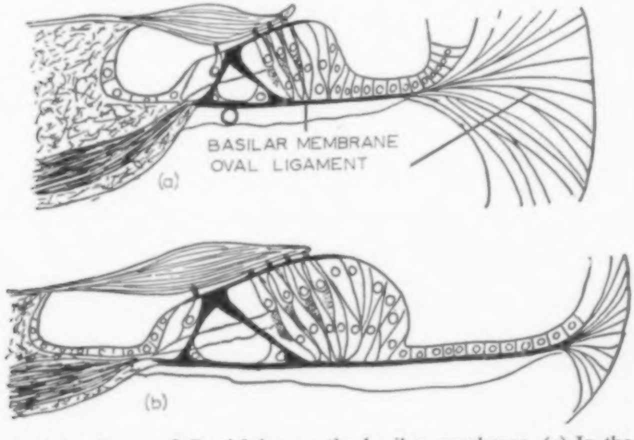

FIG. 3. Diagram of the Organ of Corti lying on the basilar membrane. (*a*) In the basal coil of the cochlea near the oval and round windows. (*b*) In the apical coil near the helicotrema. (Reproduced by courtesy of KRIEG, W. J. S. (1953) *Functional Neuroanatomy* (2nd Ed.). Blakiston Div., McGraw-Hill, New York.)

Now clearly any excessive excursion of the basilar membrane will put a strain on the hair cells which may eventually wear them out. This is what happens when the ear is overstimulated by sound. Noise being as a rule a complex sound causes general movement throughout the whole of the cochlea, but that part of the basilar membrane nearest the two windows through which the sound pressure wave enters and leaves is likely to be subject to the widest excursion and in consequence the hair cells in that part are more vulnerable than in any other. It is because of this

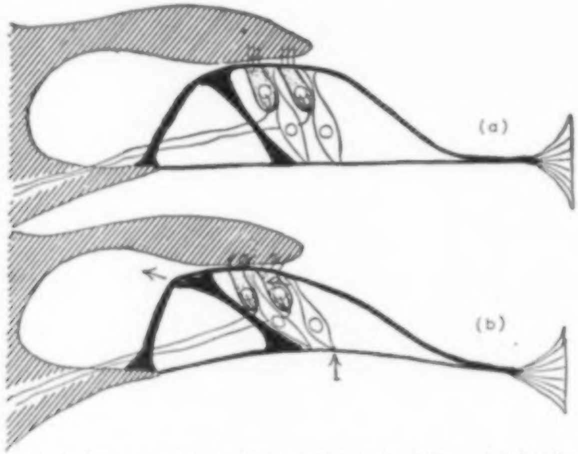

FIG. 4. Diagram of the Organ of Corti showing the hair cells projecting into the Organ of Corti. (*a*) At rest. (*b*) Being bent by the movement of the basilar membrane in response to sound pushing the Organ of Corti against the tectorial membrane. (Reproduced by courtesy of KRIEG, W. J. S. (1953) *Functional Neuroanatomy* (2nd Ed.). Blakiston Div., McGraw-Hill, New York.)

that the high tones are the first to be affected in noise deafness. The following charts are taken from a study by JOHNSTON (1953) of occupational deafness. The first (Fig. 5) shows the threshold hearing for pure tones as measured by an audiometer and is of a stamper in a foundry after he had been at work for 3 months.

The next (Fig. 6) shows the effect of similar work on a stamper after 8 years at work.

Finally (Fig. 7) there is a chart of the hearing of a chipper in a boilermaking factory after 43 years of work.

These charts illustrate the way in which hearing for high tones is first affected and this in time spreads down the hearing scale, though the lowest tones are hardly ever affected at all.

Of course, any industrial noise where the sound is concentrated within a narrow band of sound would be likely to cause a hearing defect in that area, but most factory noise is spread over the whole range of frequencies, and the deafening process then takes place along the lines shown in the charts.

A similar effect upon the hearing can follow repeated exposure to gunfire, whether this be in the cause of duty or for pleasure as in the case of shot-gun shooting.

An interesting feature about deafness from overstimulation by noise is that the sufferer often does not realize the cause of his defect. This is quite understandable

because in most instances the onset is very gradual and so long as the loss of hearing is limited to high tones only it does not cause any great inconvenience to the everyday life of the worker. Furthermore, others in the same line of work experience a similar gradual dulling of hearing and it is only too often accepted as a natural event that is to be expected in the later years of working life. This has nothing to do with presbyacusis, the natural and slight loss of sensitivity for high tones only which does not start until the late sixties and slowly increases with the years.

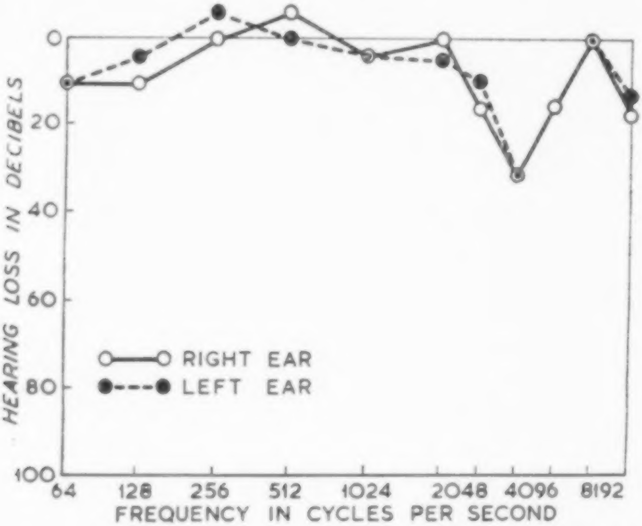

FIG. 5. Stamper, age 29. Duration of exposure, 3 months. Whispered voice heard at 10 ft distance from both ears.

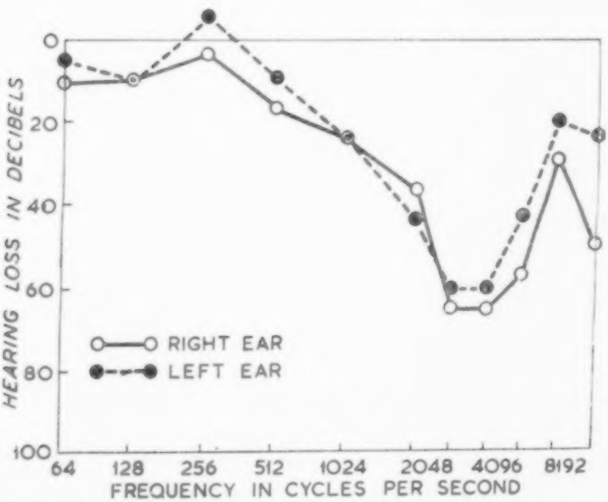

FIG. 6. Stamper, age 27. Duration of exposure, 8 years. Whispered voice heard at right/left = 1/1·5 ft distance. Conversational voice heard at more than 10 ft distance from both ears.

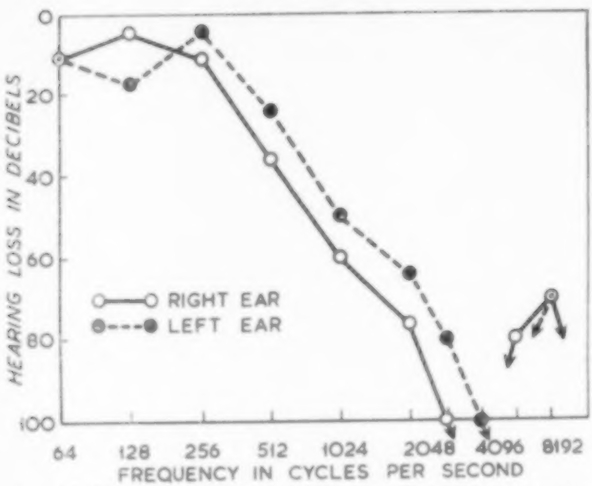

FIG. 7. Chipper, age 70. Duration of exposure, 43 years. Whispered voice heard at right/left = contact/0·25 ft distance. Conversational voice heard at right/left = 1/2 ft distance. (From JOHNSTON, 1953.)

Also many workers follow the same trade as their fathers and even their fathers' fathers, so that it may be thought to be a family failing. Consequently it has been difficult in the past to encourage workers in noisy industries to take any steps to protect their hearing.

Now the extent of the deafness in acoustic trauma and the state at which it develops depend upon three factors, namely, the intensity of the noise, the sum total of the duration of exposure, and finally individual variation in sensitivity. Much detailed information is now available concerning the character and level of noise in different industrial processes. It is generally agreed that it is not likely to be affected unless the noise level exceeds 85 phons. (The Subcommittee on Noise in Industry of the Committee on Conservation of Hearing of the American Academy of Ophthalmology and Otolaryngology, 111 North Bonnie Brae Street, Los Angeles 26, California, have prepared several useful pamphlets dealing with different aspects of the subject.)

This is for constant exposure during working life. Much louder levels can be borne without permanent harm if the duration of exposure is short.

Another important and still not very well understood factor is individual sensitivity. There can be no doubt that some ears are more easily affected by noise than others. For this reason it is important in noisy industries to try to find out which entrants are going to be unduly sensitive to noise. Those who do not readily adapt themselves to noisy surroundings, and those who cannot hear so well in a noise as their fellow workers, are likely to come within the sensitive groups; also those who are unduly troubled with head noises after a day's work.

Deliberate tests of post-stimulatory fatigue have been suggested. In such a test the ear is exposed to a pure tone at say the 30 dB level for 3 min. Afterwards this will cause a drop in sensitivity for that tone which should normally last for some minutes. Any undue delay in the return to the normal threshold of hearing for the test time is suggestive of an oversensitive ear (PALVA, 1958).

So far the effect of acoustic trauma upon hearing for pure tones only has been mentioned because this pure tone audiometer test is the simplest and most effective way of diagnosing early acoustic trauma. HOUSE (1952) has suggested pre-employment and routine periodic follow-up audiograms for workers in noisy industries. He also makes the point that the differential diagnosis of more advanced acoustic trauma after the patient has become aware of his hearing loss is much more difficult. More recently HOUSE (1957) has advocated a screening test with two tones only at 2000 and 4000.

When it comes to the relationships between hearing for pure tones and hearing for speech in acoustic trauma there is a certain amount of difficulty because in early cases when the hearing loss is limited to high tones only conventional tests of speech carried out in quiet conditions with a clear speaking voice often do not reveal any loss of hearing for speech. But this is quite different from the listening conditions of everyday life. There are no distracting outside noises and movement. There is no having to pick out the sound the listener wants to hear from other competing sounds. Also, whether in factory, office or home, the speaker, far from enunciating his words carefully and slowly, speaks with his mouth full, or with a cigarette or pipe between his lips, or from behind a newspaper. It is in such everyday circumstances that the loss of high tones may make itself felt, and there is a need for a test of the ability to hear speech in varying acoustic circumstances as well as in the quiet hearing test room. Besides quietness of the surroundings and clarity of diction there is the rate at which the speaker talks.

A hearing defect, particularly when it is due to changes in the organ of hearing, slows down the rate at which speech can be comfortably understood. Ordinary conversation is exchanged at a rate of around 180–220 words/min, while B.B.C. announcers read the news at about 160 words/min. A political speech is given at 140 words/min, and a sermon at little more than 100 words/min. Persons with perceptive hearing loss, even when it is limited to higher tones, have more difficulty in understanding all that is said to them when speech is at the higher speeds. In consequence the strain of listening often distracts their attention from the actual meaning of all of what is being said. Thus tests of the capacity to hear speech when carried out under favourable listening conditions do not always reveal the extent of the handicap in a case of high tone deafness.

In estimating the degree of social handicap in a case of deafness there is a need for a series of tests which will include the ability to hear speech in different acoustic circumstances. There is also a need for a method of estimating the degree of handicap imposed by any hearing loss. Different formulæ have been put forward for computing a percentage hearing loss based on the pure tone audiogram, but none of these is really satisfactory. A better guide is the Social Adequacy Index, which equates the pure tone audiogram with the speech audiogram. However, to get a practical result this should also take into consideration the hearing for speech under varying acoustic conditions, and a satisfactory method still has to be devised.

There is no cure for deafness due to overstimulation by sounds, so it is necessary to take all precautions practicable to prevent it happening.

The prevention of noise at source is outside the scope of this article, but where the overall noise level cannot be prevented from exceeding 85 phons workers should be provided with some form of ear protection, and they should furthermore be

encouraged in every way possible to use regularly the protective ear-plugs or headphones provided. These can be expected to offer from 10–25 phons of protection. Finally, in all noisy industries there should be some scheme for regular testing of workers from the time of entry.

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DISCUSSION

The President asked whether the figure of 85 or 90 phons was a level which should, preferably, not exist. Was it a level which was known to be non-injurious to all people or only to those people who were selected as being not ultra-sensitive? Could it be taken that 85 or 90 phons was the universally maximum permissible level of exposure or was it only applicable to those persons who were not unduly sensitive?

Mr. CAWTHORNE said that the real answer was that that figure varied from year to year. About 5 years previously it had been said that 95 dB was safe. Then it was said that 90 dB was safe, and now it had come down to 85 dB. It varied also, perhaps, from industry to industry and with the amount of exposure. The figure of 85 or 90 dB was understood to indicate that with anything beyond that level there would be a significant number of workers affected. He did not doubt that there might be a few sensitive individuals who would be affected by less.

The President said that the reason why he had asked the question was that the level seemed to him to be very high. If he had had to work in a noise at a level of 85 or 90 dB he would have found it most unpleasant and he was surprised to find that it would not actually be damaging in the course of 40 years of work.

Mr. J. W. THOMPSON (I.C.I.) asked whether the author would say a little about the effect of frequency. He personally understood that 90 dB of pure tone at 4 kc/s would be very much more damaging than a signal at 45 c/s. Could the author say whether that should be taken into account when assessing the effect of noise?

Mr. CAWTHORNE said that one of the reasons why the 4000 c/s note would be more damaging was because of the path of the maximum movement. They were really thinking not so much in terms of one noise as of a composite sound which probably had a large amount of the spectrum in it. If deliberate use was going to be made of a very loud tone at, say, 4000 c/s, it might produce more damage than any other. With a tone at 200 c/s there might still be some at 4000 as well. Most of the noise which was tested was composite noise ranging probably from 200 to 4000 c/s. Work had been done by means of deliberately stimulating animals.

Mr. R. ARCHIBALD asked whether the pattern demonstrated by the author took into account any loss of auditory purity due to advancing age.

Mr. CAWTHORNE said that he was glad that question had been asked because he had left that point out of his paper. There was a thing called paracusis, which was the increasing loss of hearing with age which was very like the increasing difficulty with vision for reading with age. With paracusis the hearing loss was akin to that caused by acoustic trauma. Probably paracusis was a general expression indicating wear and tear, and a normal person who was not in the presence of a loud sound would, at the age of 70, show a loss of about 25 dB at 4000 c/s and a loss of about 30 or 35 dB at 8000 c/s. That was normal and it was probably due to general wear and tear. Whether it would be found in 5 or 10 years' time that people of 80 suffered a greater loss than people did 30 years before, he did not know.

Dr. T. O. GARLAND (Central Middlesex Hospital) asked whether the author could say anything about expert evidence in a compensation case. He did not want him to discuss the

criteria for the assessment of damages but he would like to know whether the author, as a specialist in his subject, could go into the witness box and give clear evidence one way or the other that a person's deafness was due to his work. Any step forward in the whole matter of noise control depended possibly on the outcome of such claims. There had been 500 cases in the State of Wisconsin alone up to 1956. There had been no claims made in England as yet, but such claims would no doubt come. Was the author in a position as yet to give the necessary evidence?

Mr. Cawthorne said that one of the difficulties about giving medical evidence regarding damage was that a lawyer would ask an expert witness what the percentage of hearing loss was, and that was almost an unanswerable question. It was very difficult to assess hearing loss as a percentage. In acoustic trauma the pattern it followed was always very much the same and therefore it was nearly always possible to say that the resulting deafness was due to some form of acoustic trauma. The matter was complicated, however, by the question of individual susceptibility. Some people were more susceptible than others and that had to be taken into account. Going into court to give evidence would remain very tricky until there was some really satisfactory means of either controlling the noise or protecting the ear from the noise.

He had been present at a meeting in Boston some 3 years previously at which the Chief Commissioner for Labour in Wisconsin had said something about what had been happening there. In 1957 at Johannesburg there had been a conference on noise where the view was expressed that otologists should be able to tell the legal people exactly what percentage of hearing loss there was and how much disability resulted. Until some better tests were developed to determine how a person heard socially, he did not think it would be possible to give the evidence that they would like to give. Further tests would have to be developed and some work was being done on those lines.

Dr. Challen said that he had been in the United States some time previously and in one State it had been decided that the permissible level of noise should be 70 dB. They had then taken measurements in the city streets and found that the noise of the traffic was 75 dB. His second point was that he had been investigating noise in a factory recently and it had been found that "Music while you work" increased the factory noise by 7 dB.

Dr. Peters (Ministry of Supply), referring to noise surveys, said that she had been told that they were not of much value unless they were made by engineers. Apparently noise surveys made by medical officers were not really of value.

With regard to practical politics, at the present time it seemed that industrial medical officers who were aware of the danger of noise should ask managements to conduct noise surveys by skilled people who were competent to do so in order to find out whether the noise level was damaging or not. If it was, steps should be taken either to cut down the noise at source or to provide some form of protection. It was found in practice that there was a lack of sense of responsibility on the part of managements because they did not understand noise and they were also frightened of compensation cases. She considered that noise in factories should be evaluated in terms of noise as a hazard. They must get noise recognized as a hazard because at the moment people did not consider noise as an occupational hazard. She had been told that it was not a medical problem but an engineering one. She thought that was nonsense. She had heard of someone a few days before who had lost his hearing and she had suggested to him that he should put in a claim. He had not felt inclined to do so because his loss of hearing was not of great importance to him in his job.

There was another difficulty. A factory manager who was employing skilled men on a noisy process might find that some of his men had been employed by someone else on an equally noisy process. If one of the men became deaf the difficulty would be to know to what extent it was due to his employment in that factory and to what extent it was due to his previous employment. Managements were terrified of the workers "getting wise" to the idea. The answer was that they should face up to the problem and elevate noise to the status of an occupational hazard. She wished to ask when legislation regarding noise would take effect in England, because she had suffered in that connexion.

Mr. Cawthorne said that Dr. Peters had made some very pertinent remarks and he agreed with most of them. The word "factory" had been used as though only factories were places

where there was noise. The trouble was that there was noise in an enormous number of places and people were a little nervous of dealing with it until they knew how that noise could be brought down to a safe level.

Dr. Challen had mentioned "Music while you work". In that connexion an interesting thing had happened in a factory which he had visited. The overall noise level in the factory was about 90 phons and they had got "Music while you work" on at the same time. He and his colleagues could not hear it at all but the workers said that they could. One speaker had mentioned noise in an American street. About 2 months previously he had gone to a dancing establishment in Los Angeles where they had a 24-piece band, most of it brass, and in case that was not enough noise there was a man called Frankie Laine singing. He thought that the level of noise was above 100 phons.

Mr. D. M. A. MERCER (Southampton University), referring to the question of compensation, said that he had been discussing with the B.B.C. a plan for a broadcast on the subject and the problem of compensation had been investigated thoroughly. He thought it could be said that if compensation for noise damage came at all it would be a very long time coming because the problems were very serious, especially the legal and financial ones. The Government was very chary of opening any doors in that respect, although the trade unions were very strongly in favour. Although pressure would be brought to bear it would be some time before anything happened.

He would like to know if the author could give a figure which would indicate that a person was perceptibly deaf. The reason was that some difficulty was experienced in advising people who worked in a noisy factory. The noise could be measured and it was then possible to predict what people's hearing loss would be. The industrialist did not want information in terms of decibels but wanted a clear statement. Could the author give a figure, such as that a loss of 20 dB at so many cycles was perceptibly deaf? A figure of that kind would enable it to be said that if people worked in a certain environment they would become perceptibly deaf.

Mr. CAWTHORNE said that he did not think such a figure could be given at the moment but he hoped that it would be in the future. The nearest approach to such a figure was the Social Adequacy Index at St. Louis. That figure was quite a good one but it did not take into account the effect of listening for speech in noisy surroundings, which was an important factor. That must be added on to the present social adequacy index. He hoped that something like that would be produced in England in the not too distant future.

Mr. I. HUGHES (U.K.A.E.A.) said that the author had mentioned a figure of 85–90 dB as being the safe limit, and he would like to know whether that applied to the whole frequency spectrum or only to one particular frequency. If the noise at a particular frequency exceeded 85 dB, was that a sufficient criterion on which to say that deafness would occur?

Mr. CAWTHORNE said that he was getting somewhat out of his depth. As he understood it, 85 phons was the safe overall level of noise without referring to any particular frequency. Perhaps a physicist could answer the question better than he could.

Surgeon Rear-Admiral S. G. RAINSFORD (Ministry of Labour) said that he understood that damage to the ear was related to the total dose of noise, but he was not quite sure whether that was right. There could be a continuous noise or an intermittent noise and he would like to know whether one would be more damaging than the other.

Mr. CAWTHORNE said that according to the latest views which he had heard expressed in Boston the important thing was the total noise. Shooting was a good example of an intermittent noise. If a man shot 200 cartridges a year he would not suffer from any obvious deafness unless he happened to be unduly susceptible, but if he shot 1000 cartridges the deafness would be more pronounced and if he shot 2000 it would be still more pronounced, and so on. It was a matter of adding up the total noise.

Dr. O. MCGIRR (B.O.A.C.) asked what the author thought of the Rosenblith damage criterion and whether that could be safely applied to industrial noise. Was it an excessive level of sound for damage?

Mr. CAWTHORNE said that he had heard Rosenblith talk about that and he understood that it was a fairly good criterion. He personally would have thought it was safe.

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NOISE MEASUREMENT, ANALYSIS AND EVALUATION OF HARMFUL EFFECTS

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INTRODUCTION

When the air is agitated by noise disturbance the motion of its particles as well as the pressure variations are generally very complex in character, and a complete description of the state of affairs has to take into consideration a number of factors which include the way in which the noise is propagated, and the variation of the disturbance with time. Thus noise may be propagated mainly as a progressive wave, as in the open air, or it may have more or less random directions of propagation as well as partly stationary wave patterns, as in an enclosed space. When sound is propagated as a progressive wave the alternating changes of pressure, velocity and intensity are related by very simple formulæ, and specification of any one of these quantities embraces the necessary information on the others. Actually

$$p = 42\,v$$

and

$$w = \frac{p^2}{834}$$

where p = sound pressure in dyn/cm^2

v = particle velocity in cm/s

and w = average rate of energy flow in μW/cm^2 (intensity).

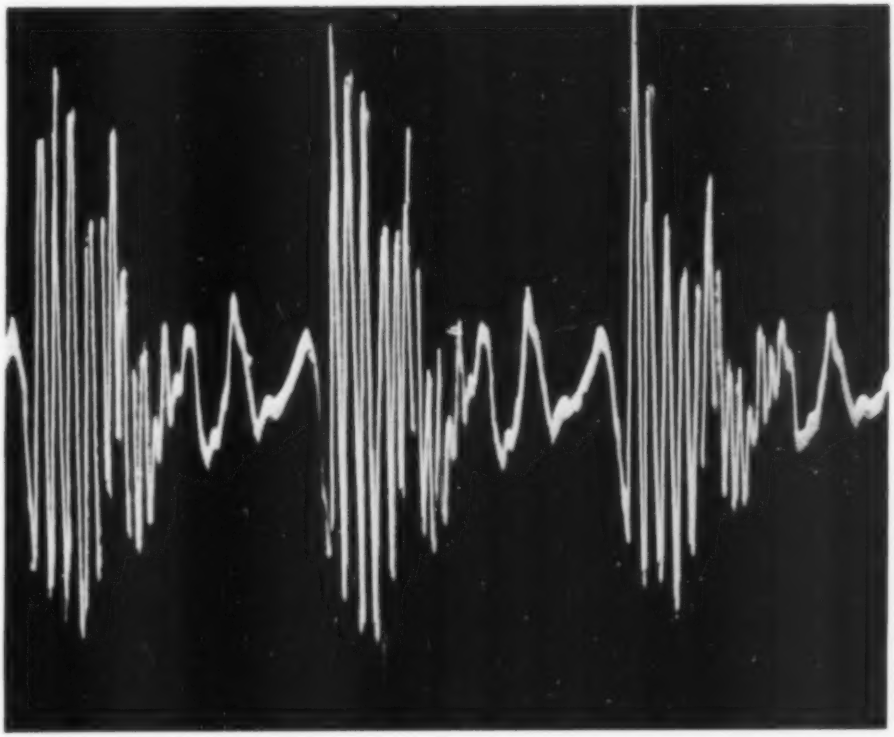
When, however, the noise is reflected by obstacles or is in a confined space these relationships do not hold and it is then possible to have what we call stationary wave conditions superimposed on the progressive sound; then we can have places where maxima of pressure variation coincide with minima of particle motion and vice versa, as well as intermediary relationships. Under these conditions it is found that the ear senses the positions of pressure maxima as those giving the positions of maximum loudness, and it is reasonably correct to say that a given pressure in a stationary wave system gives the same impression of loudness as the same pressure in a progressive system. In other words, it is the pressure variation at the meatus that is the predominating factor; that is, the ear is a pressure-sensitive mechanism, and since in this discussion we are mainly concerned with aural effects of noise, we are chiefly interested in the variation of acoustic pressure of a given noise situation. Its variation with time may be somewhat random or it may have pronounced periodic characteristics. For example, the noises from jet aircraft or hissing steam have not the periodic characteristics present in the noise produced by propeller-driven aircraft, weaving machines or pneumatic drills.

Under average normal conditions the pressure of the atmosphere is about 10^6 dyn/cm², but when it is under the influence of a sound disturbance the pressure fluctuates above and below this average, the fluctuation being the acoustical pressure referred to earlier. For a very intense sound such as that close to a jet engine the variation may be of the order of 2000 dyn/cm². It is now established practice to express the intensity of sound as the amount in decibels above the arbitrary oscillatory pressure of 0·002 dyn/cm², known as zero sound pressure level, or 0 dB S.P.L. An intensity change of 10 times, which is the same as a pressure change of $\sqrt{10}$ (=3·18) times is defined as a change of 10 dB. In this case an acoustical pressure of 2000 dyn/cm² is a pressure change of 10^7 times or an intensity change of 10^{14} times and is said to have a sound pressure level (S.P.L.) of 140 dB. The state of the sound disturbance is expressed physically as the variation of this acoustical pressure with time and it can be recorded visually as a curve of instantaneous acoustical pressure against time, what we understand as the wave form of the sound. Fig. 1 shows wave forms of a repetitive sound and a random noise. The wave form of a musical sound or a vowel has a regular frequency of repetition or fundamental frequency; similarly, for most mechanical noises there is some activity which has a cycle of occurrence, as in a loom or rotating machinery. On the other hand, some noises have a random or sporadic character and the most powerful source of this nature which at present causes concern is the modern jet engine, especially when maintenance personnel have to work in close proximity for appreciably long periods.

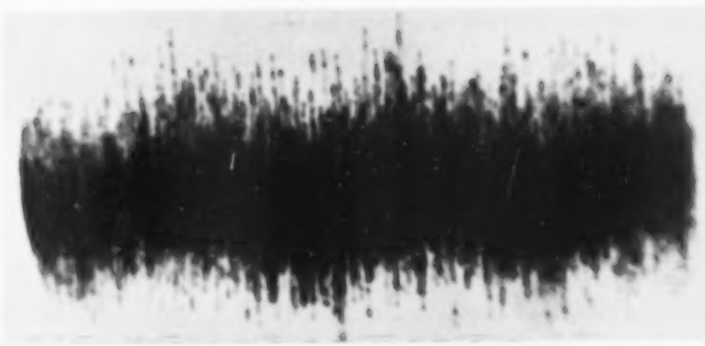
Now a tremendous amount of work has been devoted during the last 25 years to the study of the effect on hearing of exposure to intense sound. This work, in addition to providing information on the actual effects produced, has added to our knowledge of the behaviour of the ear in general, but at the same time it has brought to light certain peculiarities in behaviour which are difficult to explain.

SOUND-LEVEL MEASUREMENT

The wave forms of the sounds and noises give curves of sound pressure variations which vary above and below the normal in minute fractions of a second, what we could call cross-over fluctuations; the positive and negative pressures also fluctuate, and as well there can be a slower variation of the curve as a whole. If this variation is sufficiently slow it can be sensed by the ear as a definite change in intensity, and the order of time required to be sensed as a variation of this type is dependent on a number of factors. In addition, if there is a sudden increase or decrease of the average intensity this will also be sensed as a transient change and may produce certain physiological effects. It will be seen from these remarks that it is not to be expected that a few figures can be given for the noise of a given situation that will express all the physical and physiological characteristics associated with it, and so the subject is one constantly under review. As well as the ear, physical measuring instruments may have their own time-response characteristics. Strictly speaking we can only specify a given noise accurately by giving the wave form exactly, but there are one or two important characteristics which we can specify which give very valuable information. One of these is known as the root mean square (r.m.s.) value of the sound pressure level; it is an average of the sound pressure fluctuation taken over a certain short interval. Another characteristic is the peak sound pressure level, which is the highest value attained by the



(a)



(b)

FIG. 1. Wave forms of sounds; (a) repetitive sound, (b) random noise.

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acoustic pressure during a specified interval. A sound which has a few high peak pressures might therefore give a high value for peak pressure but a low r.m.s. pressure, whereas a very loud smooth sound might give a lower peak level and a very high r.m.s. level. In the case of the smoothest sound possible, namely the pure tone, the ratio of peak level to r.m.s. level is 1·4 ($\sqrt{2}$), whereas for a series of short pulses the ratio can be very high.

In determinations of r.m.s. and peak values of noises it is necessary to consider the intervals to which these quantities refer, and so physical equipment is used with time factor limits which are considered reasonable, according to the particular situation, the time of response of such equipment giving the order of the interval over which the r.m.s. computation or the peak determination is made. In some instruments where a noise is fluctuating rapidly, slow-moving indicators are deliberately incorporated to smooth out these fluctuations. Standardization of these characteristics is receiving the attention of British and American standardizing committees.

NOISE ANALYSIS

A given wave form can be analysed into other equivalent wave forms in a number of ways, the one that is the most fascinating and most elegant being known as the Fourier transformation. In the Fourier transformation a sound or noise is represented as made up of an extended range or spectrum of frequencies of pure tones. In certain special cases of sustained repetitive sounds the Fourier analysis is one of discrete frequencies but, in general, the noise spectrum is made up of an infinite range of frequencies. A given sound is then said to have a spectral level at each frequency which represents the amount of energy that is assigned to the frequencies within a band 1 c/s wide centred at the specific frequency. In Fig. 2 we have examples of the analyses of a number of wave forms by Fourier transformation. In practice a precise analysis requires special equipment and is not justified when one takes into consideration the physiological behaviour of the ear, and an approximation to a Fourier analysis is made by introducing elements known as filters in the measuring system which are only effectively responsive to certain limited frequency ranges or bands of frequencies. These ranges can be restricted or wide according to the detail required of the analysis. The narrowest band practicable is that of a few cycles wide, and such a filter is used to give an approximation of the spectral level or sound pressure level per cycle band, e.g. if the filter is 10 c/s wide the spectral level is 10 dB below the total sound pressure level of the 10 c/s band. Other filters in use are octave band or fractional octave band filters and it is general practice nowadays to specify the boundaries of octave band analysis at the frequencies 37·5, 75, 150, 300, 600, 1200, 2400, 4800 and 9600, with fractional octave limits at intermediate frequencies. Such a wide band filter gives the *total* sound pressure of the noise contributed by the energy of all the constituents in the band and does not indicate the average level in the band, and so wide band filters may give misleading figures of the physiological effects in special cases where intense single tones or narrow bands are present. A very intense narrow band, if present, may be responsible for almost the whole of an octave band analysis. Since there is some evidence to suggest that intense narrow band noises might be more traumatic than wide band noises of the same sound pressure level, it is suggested that a narrow band analysis is always a useful procedure where a noise has a definite

repetitive characteristic. Fig. 3 gives the analysis of a repetitive wave form by selective filters, and Fig. 4 the analysis of random noise by filters of various selectivities.

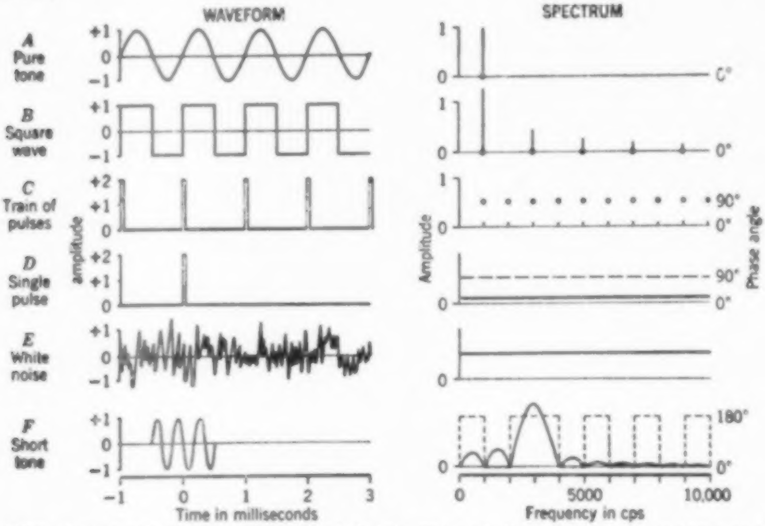

Fig. 2. Wave forms and spectra. In each of the six pairs of diagrams the wave form at the left showing amplitude as a function of time provides exactly the same information as the spectrum at the right showing both amplitude and phase angle as functions of frequency. The wave form graphs are to be thought of as extending indefinitely in both directions. The spectrum graphs are to be thought of as extending indefinitely to the right. Amplitude (solid lines) is specified in arbitrary units; phase angle (broken lines or heavy dots) in degrees. Reprinted with permission from Licklider (1951).

In a practical noise survey it is customary to specify the overall sound pressure level by measurement with a sound level meter having a range from a few cycles per second to about 10,000 c/s and then to supplement this by information on the contribution of the various frequency bands with, where it is considered important, a spectral analysis.

At times the comprehension of additive effects of noise components may be confusing. For while noises are expressed in sound pressure levels, it is the intensities of components that are additive. Consequently, when it is necessary to assess the sound pressure level of the combined effects of different contributory noises, the individual noises must first be converted to intensities, after which they can be added together and converted back to a sound pressure level. Thus, two noises each of S.P.L. 90 dB produce a noise of twice the intensity of either, which is 93 dB. A noise of 100 dB combined with one of 90 dB produces a resultant noise of about 100·5 dB. Such additions are often made easier by the use of tables.

RESPONSE CHARACTERISTIC OF THE EAR

While the human ear can differentiate sounds of slightly different frequencies it does not behave like a selective filter in so far as a pure tone of a given frequency excites a considerable region of the analytical system of the cochlear partition. Theoretical and experimental work seems to point to selective analysis as being

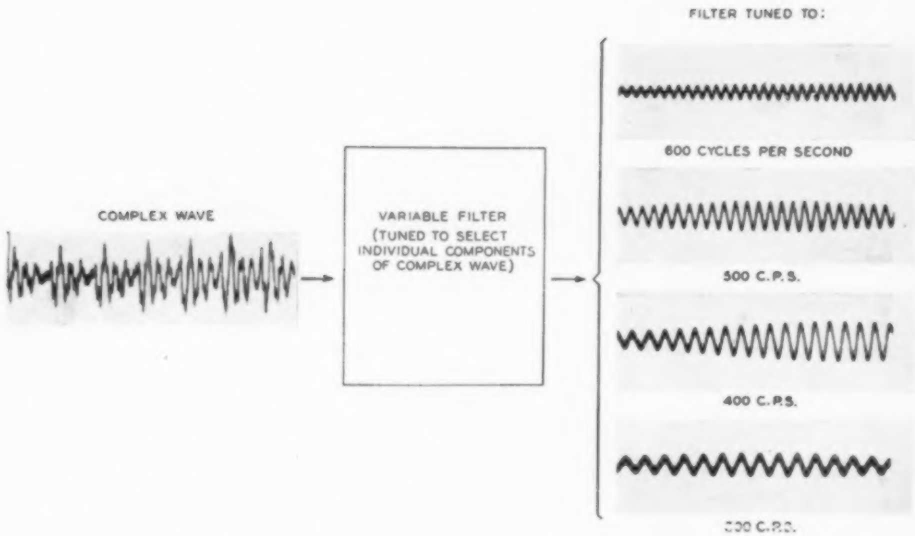

FIG. 3. Analysis of repetitive wave form (after POTTER, KOPP and GREEN (1947) *Visible Speech*. Van Nostrand, New York).

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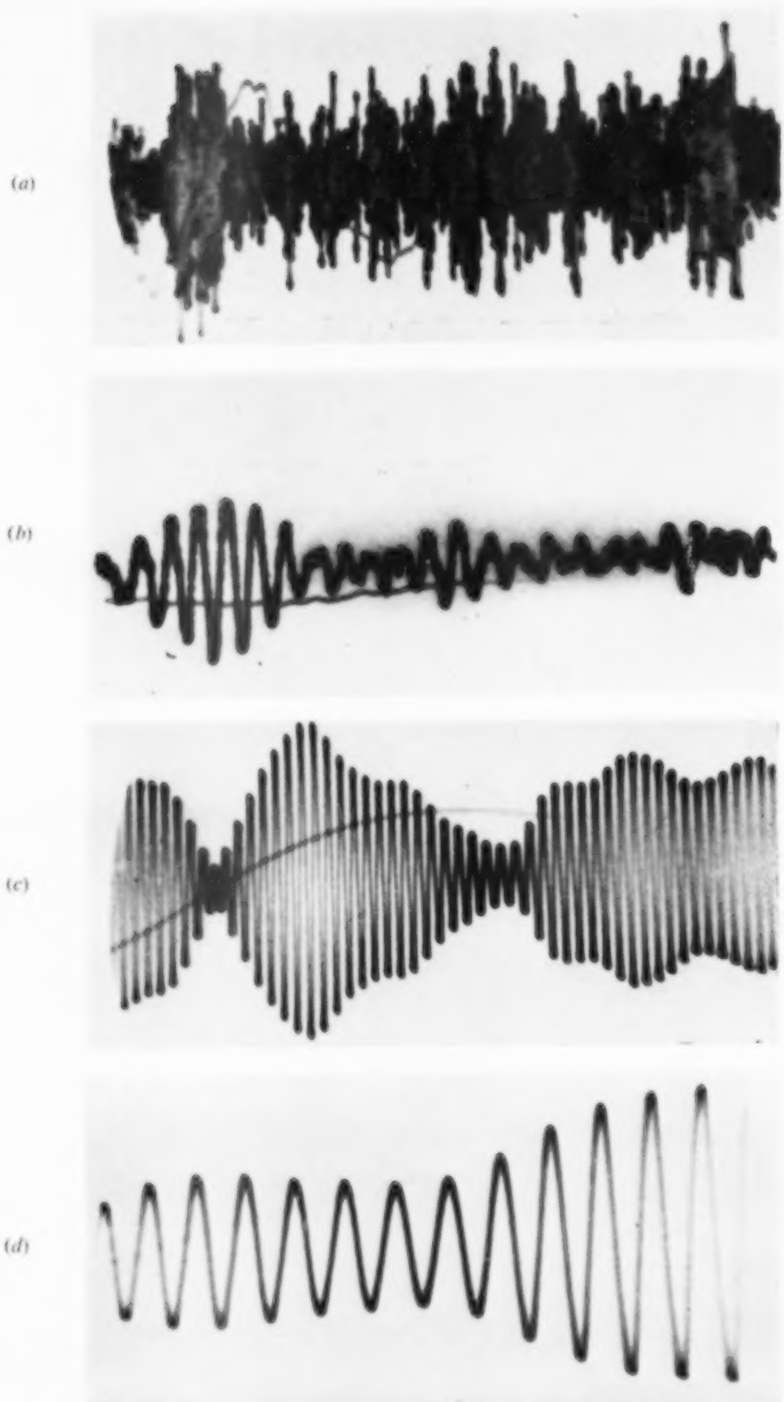


FIG. 4.. Analysis of random noise. (*a*) One third octave band centred around 4000 c/s (50 m trace); (*b*) one third octave band centred around 500 c/s (50 m trace); (*c*) band of few cycles wide centred around 1000 c/s (50 m trace); (*d*) as (*c*) but (15 m trace).

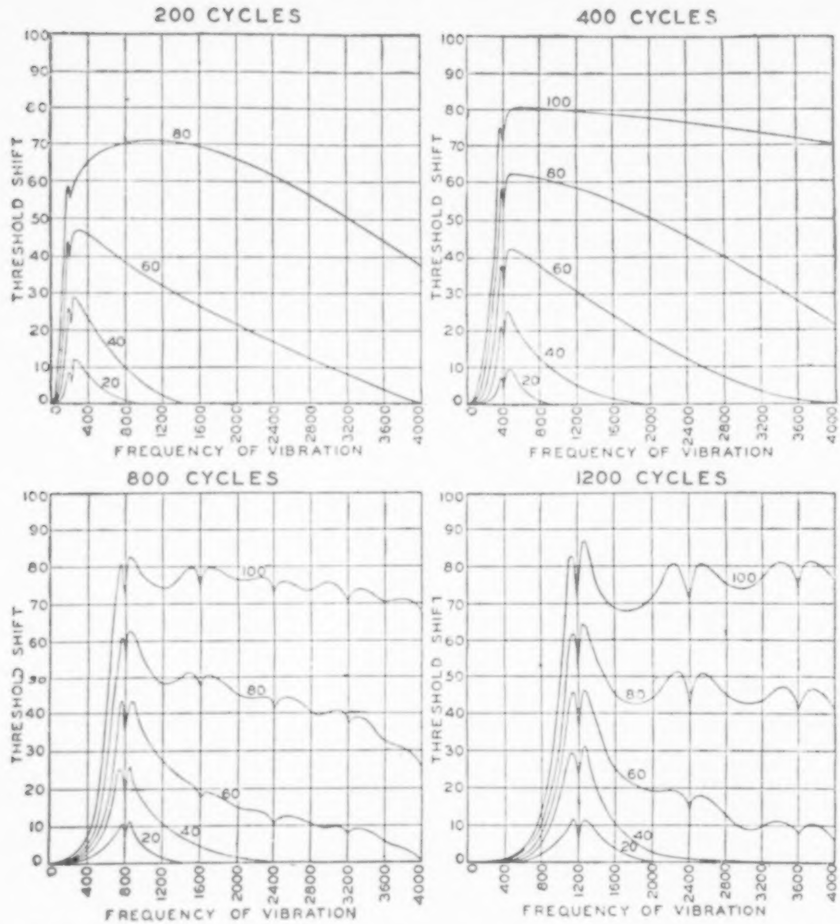


FIG. 5. Masking of pure tones. The ordinates give the threshold shifts of test tones indicated by the abcissæ when masking tones of 200, 400, 800 and 1200 c/s respectively are applied at sensation levels from 20 to 100 dB.

due to the combination of the selective action of the cochlea and the neural pathways, but as far as damage to the cochlea is concerned it is probably the mechanical disturbance in the cochlea that is important. The work of the Bell Telephone Laboratories, particularly that of FLETCHER (1929, 1930), and of WEGEL and LANE (1924) about 30 years ago, pointed out the likely behaviour of the mechanical system of the cochlea, which was later supported by the remarkable series of direct observations of BÉKÉSY (1942) and the experimental work of WEVER and BRAY (1930), DAVIS *et al.* (1946) and TASAKI *et al.* (1952). Some of the famous curves of WEGEL and LANE (1924) on the masking of one pure tone on another are given in Fig. 5; near the threshold the masking extends to a narrow band around the masking tone, but at high intensities the extension to tones higher than the masking tone is abundantly clear. The results of the direct observations of BÉKÉSY (1942) are

shown in Fig. 6. Note that all elements of the cochlear partition between the peak excitation and the fenestra regions are excited, whereas those nearer the helicotrema are quiescent. In the region excited, BÉKÉSY observed a wave travelling from the fenestra towards the limit of excitation. The sharp demarcation probably gives the region of specificity, but note that if this is the case the region maximally disturbed would correspond to a higher frequency of specificity. This explanation would support the experimental observations that a very intense pure tone is

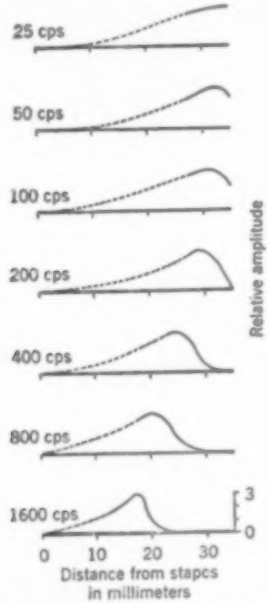


FIG. 6 (*a*). Displacement amplitudes along the cochlear partition for different frequencies. The stapes was driven at a constant amplitude and the amplitude of vibration of the cochlear partition was measured. The maximum displacement amplitude moves towards the stapes as the frequency is increased (BÉKÉSY, 1943).

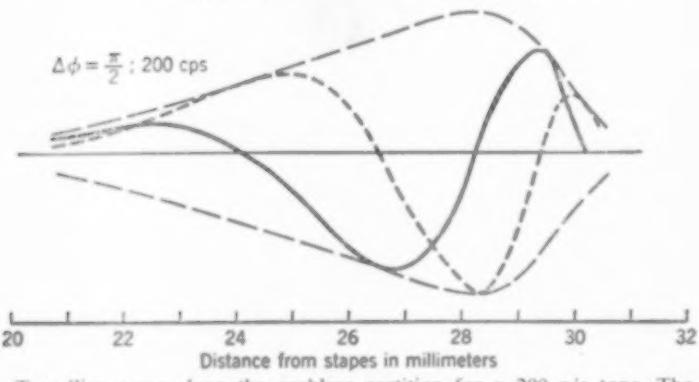


FIG. 6 (*b*). Travelling wave along the cochlear partition for a 200 c/s tone. The solid line indicates the deformation pattern at a given instant. The line with the short dashes shows the same travelling wave $\frac{1}{4}$ of a period later. The envelope shows the maximum displacement at each point (BÉKÉSY, 1947).

sometimes found to produce most auditory fatigue in the regions of the ear specific to a frequency about half an octave above the fatiguing tone. Although the extended response of the ear is generally biased towards the higher frequencies, the excitation gradually diminishes from the peak excitation to those regions distant from the region of specificity. These direct observations of Békésy (1942) are supported by the observations of Tasaki *et al.* (1952) of the magnitude of cochlear potentials at selected regions of the guinea-pig cochlea.

From these observations it seems reasonable to conclude that, while a noise which is made up of intense low-frequency energy could be expected to produce damage to higher specific frequency regions of the cochlea, it is unlikely that intense high-frequency noises will have serious effects on lower specific frequency regions.

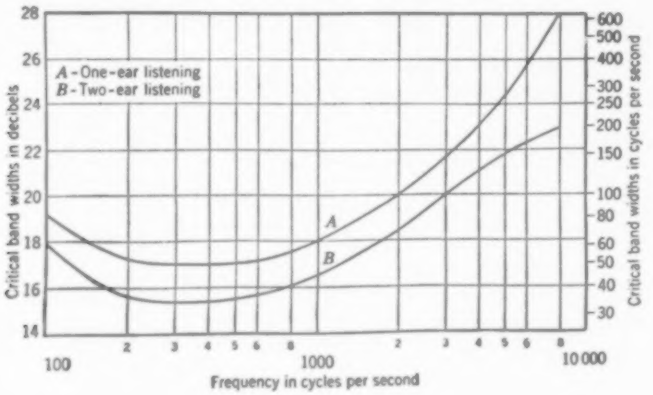


Fig. 7. Critical band widths.

Experimental work by Fletcher (1930) has shown that, for most noises in practice, a pure tone is masked mainly by a limited band of frequencies centred around the frequency of the pure tone. This narrow range of frequencies has been called the critical band by Fletcher (1930), and Fig. 7 gives a curve showing the extent in cycles over the audible range as estimated by French and Steinberg (1947). It can be seen to vary from about 30 c/s to 200 c/s for two-ear listenings, or as 15–30 dB added to the spectrum level. Now it is quite possible that this conception will not apply if we are concerned with noises having spectral responses increasing very rapidly on one or both sides of a given frequency, but it remains approximately true for the type of noises generally encountered in industrial situations. As far as damage to the ear is concerned it appears reasonable to suppose that the critical band should be the one that is effective for a given frequency region of the ear, and some authorities suggest that critical band levels should be examined in exploring the likely hazard from an industrial noise. Another body of opinion, however, suggests that, in order to get the trend of noise hazards, it is sufficient to determine octave band analyses. In this connexion there has been an excellent investigation carried out in 1954 by a Committee of the American Standards Association, which put forward views that hearing loss at a given frequency might be correlated with the amount of noise in an octave band below

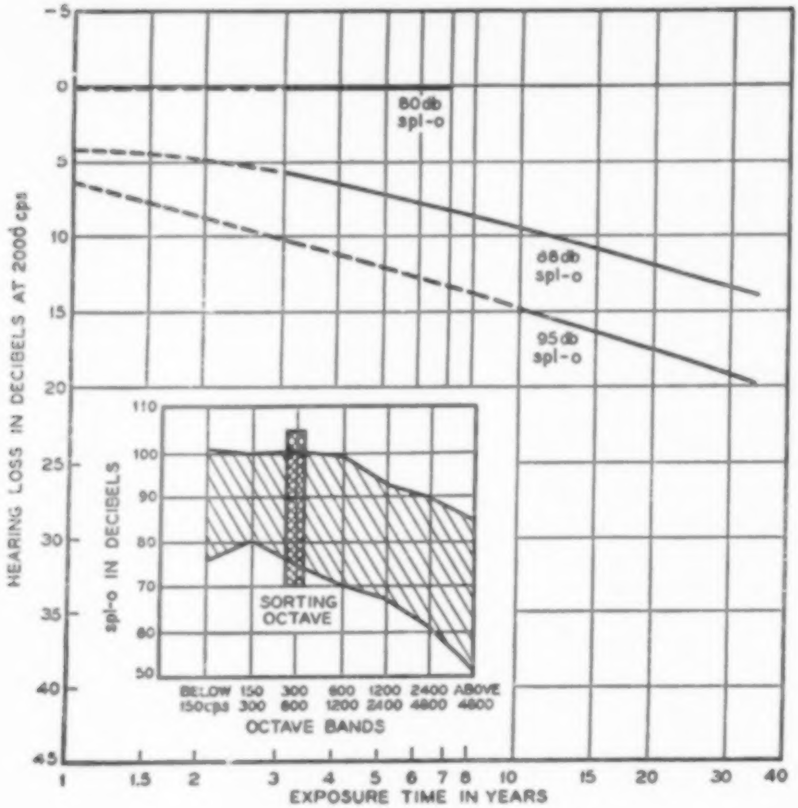


FIG. 8. Estimated average trend curves for net hearing loss at 2000 c/s after continuous exposure to steady noise. The parameters on the 3 curves represent the S.P.L. in the sorting octave 300–600 c/s. (From Z.24 Report, American Standards Association.)

that frequency. Figs. 8 and 9 show some of the results of that survey which are embodied in the report *Relations of Hearing Loss to Noise Exposure.* As in other investigations, very wide variations of individual susceptibilities were found in this study.

From the spectrum level curve of a noise we can get either the critical band level or the octave band level by adding together the contributions from each cycle band width of the noise, and if the spectrum level has no sharp peaks we can get the critical band level by adding on to the spectrum level a figure in decibels corresponding to the critical band, e.g. if the critical band is 100 c/s the figure to be added is 20 dB, as indicated in the alternative ordinates of cycles and decibels in Fig. 7. We cannot, however, determine critical band levels from octave band analyses unless the noise is fairly uniform throughout the octave bands. Fractional octave band analyses, however, give a more detailed picture. Now, as we are still ignorant of all the responsible factors contributing to noise trauma it is suggested that a narrow band analysis is always a useful adjunct to octave or part octave analysis

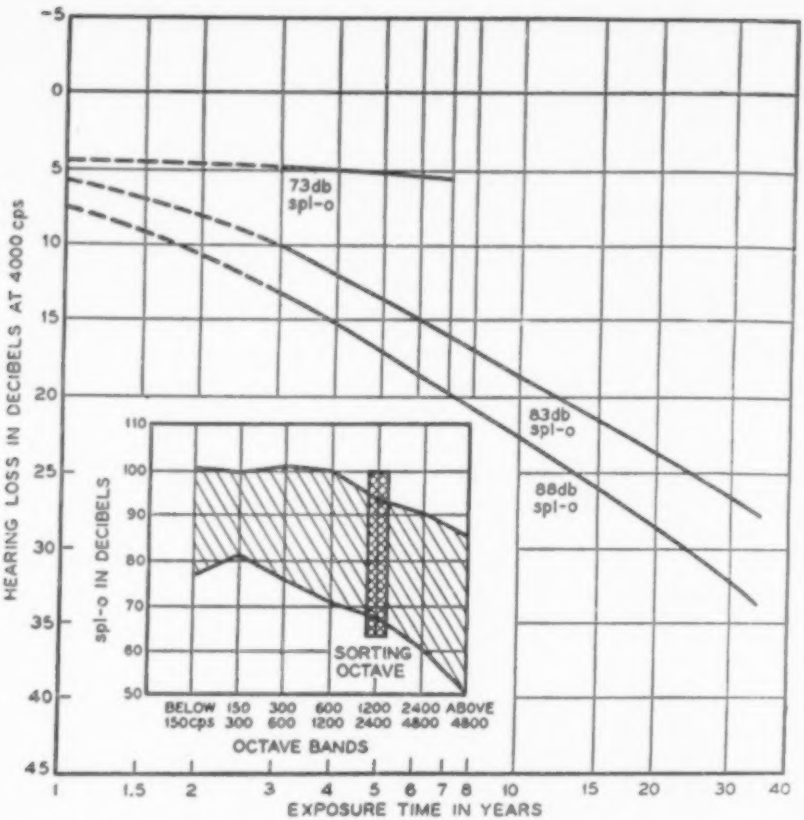


FIG. 9. Estimated average trend curves for net hearing loss after continuous exposure to steady noise. The parameters on the three curves represent the S.P.L. in the sorting octave 1200–2400 c/s. (From Z.24 Report, American Standards Association.)

in so far as the former will locate any intense components in narrow band widths, as suggested earlier in this paper. It is to be expected that if a sound level is entirely devoted to a pure tone, it will produce more localized excitation of the cochlear organ than if its energy is distributed over an extended range. A narrow band analysis is also useful in the location of a group of frequencies that have a common fundamental frequency which may point to a sharply rising wave form, which some workers consider to be a particularly traumatic noise.

As different noises of the same sound pressure levels may affect the ear differently, it has been suggested that subjective impressions should be taken into account in assessing the nuisance value of a noise. It has been found, for example, that a sound having a number of pure tone components appears louder than a pure tone of the same sound pressure level, and so the concept of the phon levels of loudness has been suggested as a more realistic attribute of noise excitation and with the phon scale we have the associated sone scale, which is referred to in the paper by FLEMING and COPELAND (1958).

DETECTION OF HEARING IMPAIRMENT

Surveys of normal hearing

In considering the amount of hearing impairment which occurs as a result of noise hazards it is of great importance to ensure that the standard of normality is clearly understood. A number of surveys and investigations have taken place to obtain a standard of normality, and it would not be possible in this paper to do more than discuss this subject very sketchily. Some of these assessments are given in Fig. 10. In 1933 SIVIAN and WHITE surveyed the information then available and gave a curve of minimum audible sound field pressure. Many other surveys have been made since, but the most important one as far as this country is concerned is that made by DADSON and KING, of the National Physical Laboratory, from 1946 onwards at the request of the Medical Research Council. This work, supported by a later investigation by WHEELER and DICKSON, was ultimately used as the basis of the British Standard. The position had, however, been complicated since the work of SIVIAN and WHITE by various surveys in the U.S.A. which were responsible for the establishment of the American standard, which specifies a hearing level of the order of 10–15 dB higher, that is, less stringent than the British.

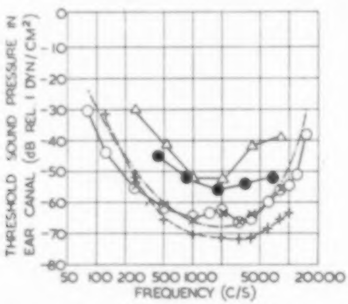


FIG. 10. Minimum audible pressure at the entrance to the external auditory meatus—modal value for 198 ears showing comparison with ear canal measurements by other investigators.

— — — SIVIAN and WHITE (1933)

△ U.S. Public Health Service } ear canal pressures as given by

● World's Fair Tests } STEINBERG *et al.* (1940)

○ DADSON and KING (1952)

× WHEELER and DICKSON (1952)

+ CHAVASSE and LEHMANN (1956, 1957)

Reprinted with permission from ROBINSON and DADSON (1957).

Audiometers, which are the instruments used for testing hearing, have their zeros set so that the reading is 0 dB at the sound pressure levels estimated to be the normal threshold of hearing, and here it should be stressed that the decibel readings on audiometers refer to the appropriate standard of normal threshold and are not sound pressure levels. Now we have a great deal of information, which has accumulated during the last few years, on testing with audiometers which are based on the American standards, and there is no doubt that the modal values of young normal subjects give results which are nearly 10 dB too optimistic, i.e. they respond to −10 dB on the audiometer instead of 0 dB (in this respect the readings refer to indicated hearing loss, and 0 dB on an audiometer should be close to the modal value found in practice). In addition, we have experience of testing young

normal subjects on an audiometer based on the British Standard and we have obtained modal values between 0 and 3 dB above the British Standard. Now, since modal values in the British Standard have been determined on 2 dB steps whereas most present-day audiometers have 5 dB steps, it is to be expected from statistical considerations that there would be a tendency for a modal value to be a few dB higher, on the ground that a subject who just cannot hear a setting will require a 5 dB higher level, whereas one who hears a setting which is a few dB above his threshold will not respond to one which is 5 dB below. There would therefore be a bias towards higher readings than the true ones. Thus, all this work lends support to the British Standard as the more accurate and representative one. We understand that some continental countries also get values closer to the British than to the Americans. Since both American and British standards specify the acoustical pressure at the meatus, inter-conversion of results is simple; it would seem, therefore, that the existence of these two different base-lines, though an inconvenience, need not detract from any noise hazard survey as long as we state precisely our reference for zero hearing loss or, alternatively, give hearing responses as absolute sound pressure levels. In all surveys at present undertaken in this country it is customary to use as controls a group of subjects who have not been subjected to a noise hazard, and in this way it does not really matter what audiometric base-line

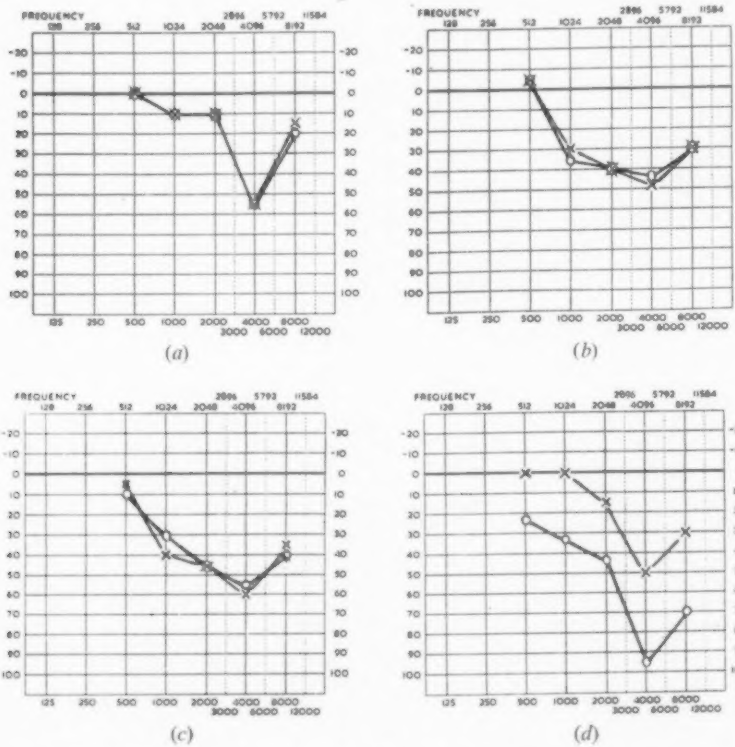


FIG. 11. Audiograms of workers in industrial noise. (*a*) Age 34, 20 years' weaving; (*b*) age 46, 33 years' weaving; (*c*) age 21, 2 years' spinning; (*d*) age 25, 9 years' weaving.

is used. However, as time goes on and more and more industrial surveys are inaugurated it is hoped that a satisfactory base-line of normality will become established and the requirement for large control groups, in some ways a waste of effort, will disappear.

Audiograms of personnel subjected to noise

Fig. 11 and Figs. 5 to 7 in Mr. CAWTHORNE'S paper (1958) show a few audiograms of workers in different noise situations, from which it will be seen that there are different degrees of hearing loss not necessarily correlated with the length of exposure. There is one particularly striking characteristic which is that, quite often, there is a notch in the audiogram round about 4000 c/s. This is known as the traumatic dip or notch and it is not necessarily located precisely at that frequency, but is always reported near that frequency because it is one of the fixed audiometer frequencies and the usual neighbouring test frequencies are 2000 c/s and 8000 c/s; however, some observers test at additional frequencies of 3000 c/s and 6000 c/s. Some of the deafness curves show a more uniform loss, however, the reason for which is the subject of further research. It may be that the notch is generally associated with periodic, or even irregular, impulsive sounds, and in this case the natural resonance of the meatus (about 3500 c/s) may be responsible for determining the rate of rise of the wave front, or for producing transient effects. Fig. 12 shows the results of ROBINSON and DADSON for equal loudness contours. On each curve there is a notch with a minimum around 3000 to 4000 c/s in a free field. The same kind of notch is observed in other studies. This apparently shows that the ear requires less energy over that region than for any other frequency to experience a certain sensation of loudness. Originally it was believed that resonance of the meatus was appreciable here, but there is now evidence that diffraction of the head might

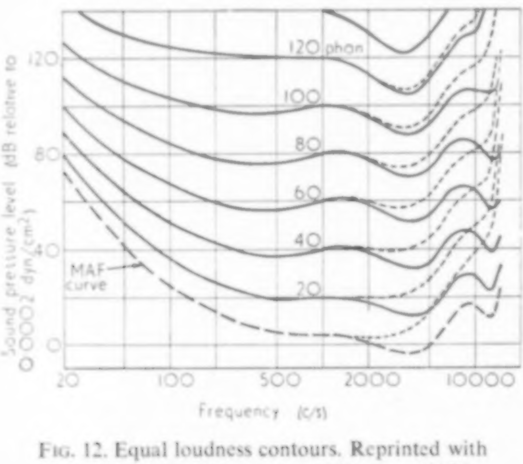


FIG. 12. Equal loudness contours. Reprinted with permission from ROBINSON and DADSON (1956).

be an additional contributory factor. One might therefore think that all noises would be weighted in their effects to this same magnitude and to a certain extent this would be true, but the effect of a noise on the ear is compounded of the individual properties of the ear together with the special characteristics of the noise. In the

latter, there may be spectral characteristics which give more emphasis to one particular region of frequencies than another, and if this emphasis is sufficiently great then we should expect more damage to that specific, or a somewhat higher, frequency region than to other regions. However, it should be pointed out that most studies of the ear are made with steady pure tones, whereas the ear and some sources of sound have definite transient characteristics. Békésy (1942) has shown, for example, that when a sudden pulse is applied to the ear the ossicular chain performs a transient vibration; there is a latent period while the movement of the drum and ossicles are building up their response with definite frequency characteristics and there is a similar effect when a sound is suddenly stopped. The sound from gunfire also has transient frequency characteristics influenced by the natural resonance of the gun barrel and muzzle and, here again, the transient sound emitted will have a definite time of rise governed by the characteristics which will probably influence the region of maximum excitation of the cochlear partition. On the other hand, there does not seem to be the same tendency for random noises such as those of jet aircraft to produce as much cochlear damage as that produced by propeller aircraft or machinery with a definite frequency of recurrence. This may be due to the fact that random noises produce a general turbulent pattern of disturbance along the cochlear partition and so there is no sustained or partly sustained pattern. Such an hypothesis is supported by wave form analyses of random noises as illustrated in Fig. 4, where it is found that a steady pure tone amplitude is never approached however narrow the selectivity of the analyser. An oscillograph record always shows a fluctuating envelope which has the appearance of a sine wave whose amplitude fluctuates in an irregular manner, the number of fluctuations per second being of the order of the band width.

It is only by long-term experimental work on a large scale that we can expect to derive useful information on the various factors involved, one of the great difficulties in this type of investigation being the isolation of the various contributory causes of industrial deafness. There may be pathological changes, which to a certain extent can be eliminated by medical examination. Quite often exposure to gun blast, or other noises of warfare, might be more traumatic than a particular noise under investigation. In fact, very often, only a small fraction of personnel under study can be brought into consideration in these investigation.

Methods of ear protection

Assuming that everything has been done to reduce the noise at source, and to employ as much screening and muffling as possible, it remains to consider effective ways of isolating the ear from the noise by insert ear plugs or external ear muffs. When an insert ear-plug defender is used, the main path of entry of sound to the ear is by the cartilaginous surround of the meatus which excites the conductive mechanism. If the auricle is covered by an efficient ear muff, then the impact of sound on this most permeable region is reduced. There is a limit beyond which a combination of ear plug and insert is effective, after which the ear is excited by bone conduction of the whole skull. It is estimated that this bone conduction excitation is about 50–60 dB below the other forms of ingress and consequently it need not, at present, be considered an important contribution to a noise hazard since the best forms of ear defenders have an insulation factor which is still below

this figure. Examples of the two forms of defenders are illustrated in Fig. 13, and Table 1 gives figures of insulation for frequencies over the audible range. Most external muffs suffer from the fact that the padding surrounding the auricle is rather

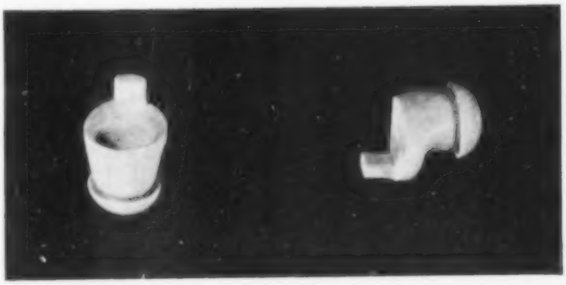
TABLE 1. SOUND INSULATING PROPERTIES OF EAR DEFENDERS

Frequency band (c/s)	Sound reduction (dB)	
	Insert	Ear muff
Below 150	10-15	20
150- 300	20	25
300- 600	25	33
600-1200	25	40
1200-2400	30	42
2400-4800	30	45
Above 4800	35	40

porous and so sound has access to the meatal opening. In the form of defender designed by SHAW and THIESSEN (1954), however, the surround is a fluid sealed in a flexible plastic and so far this is the greatest contribution to good external insulation. Even with this comfortable and efficient defender there are occasions where the contours of the bony surround the auricle are so irregular that a leak occurs unless the pad pressure is high. Particularly is this so in the region where the mandibular joint is attached below the tragus, and a better seal can be ensured here by the use of a strap under the chin. An improvement that might be worth while would be the use of a boss on the bowl of the ear muff in this region before the fluid seal is attached.

Audiometric programme of hearing conservation

It has been pointed out that there are differences of susceptibility of individual ears. In recent years so-called Damage Risk Criteria have been put forward with the object of avoiding hearing loss due to exposure to industrial noise. The first, proposed by KRYTER, was later modified or refined by ROSENBLITH and STEVENS. Then came the American Z.24 report of the investigation referred to earlier in this paper, which gave trend curves of noise levels likely to produce given average hearing loss after a number of years' exposure. After examination of this report, W. BURNS and the author suggest the specification of a noise as figures of sound pressure levels in the 8 octaves which, if not exceeded during the working day, can be expected not to cause deafness in an unspecified majority of people. Levels which are 5 dB greater than these throughout the range would be expected to produce a hearing loss, on the average, of about 3 dB at 1000 c/s, 6 dB at 2000 c/s and 9 dB at 4000 c/s, if applied for 10 years throughout the working day. It should be pointed out that this specification gives an hypothetical noise spectrum and that any given noise situation may exceed the criterion in some regions and be below it in others. It is reasonable to expect that some relaxation might then be made in the permissible maximum of one region for a lower noise level in another, but it would be difficult to say anything precisely on this matter at present. The recommended maximum permissible levels are shown, together with the Rosenblith and



(*a*)

(*b*)

FIG. 13. Ear defenders. (*a*) Insert type; (*b*) ear muff type.

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Stevens criteria, in Fig. 14. Until further knowledge is acquired they can only be looked upon as very tentative.

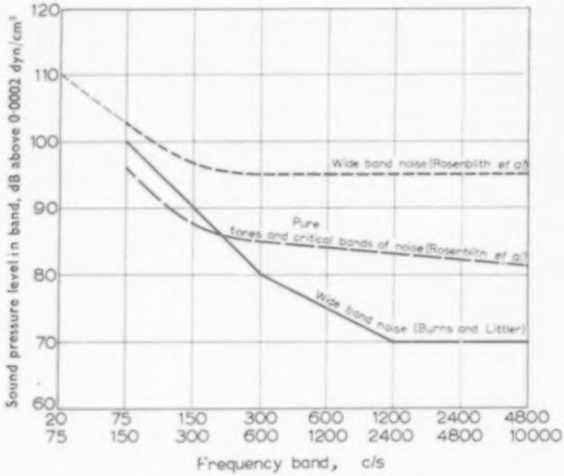

Fig. 14. Damage risk criteria.

So far there is no satisfactory easy method of predicting the hearing loss likely to be sustained by a given individual in a particular noise situation. If there is any suspicion that there might be a noise hazard, the only reasonable attitude to adopt is the acceptance of a noise control programme which would include protection of the ears and systematic audiometry. Since, in addition to industrial noise, there are other factors which might be responsible for the onset of deafness, and particularly if legal responsibility for hearing impairment is likely to be called in question, it is important to observe the hearing efficiency of personnel before and during the course of their employment. An otological examination should precede any audiometry to ensure that there is no meatal obstruction or other medical factor which might vitiate the accuracy of the hearing loss assessment. By such a programme of audiometry, in association with the provision of ear protectors where necessary, personnel particularly susceptible to noise trauma can be detected and their hearing conserved. In passing, it should be emphasized that noise in an audiometry testing room should not be so high that critical band levels mask the zeros of the audiometer. Deafness due to industrial hazard is perceptive, and so if air conduction audiometry reveals a hearing loss it is advisable to perform a bone conduction test as well. Conductive deafness can be attributed to other ætiology and to a certain extent acts as a protective measure against cochlear damage due to noise.

We have not sufficient knowledge at present to say whether a person already deaf will be as vulnerable to noise as a normal, nor whether a deafness produced by noise will progress should the subject be removed from the noise. It could, however, be argued that a person who is conductively deaf would be less liable to noise trauma than a normal or perceptively deaf subject. The American Committee gave the opinion that progress of deafness was always added to any perceptive deafness: in other words, perceptive deafness is not a protective disability.

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DISCUSSION

Mr. J. V. Morris asked whether there was any advantage in the type of ear defender described by the author over the P.V.C. type 51.R.

Dr. Littler replied that the P.V.C. type seemed to harden more than the present ones. The old rubber ones with carbon black were flexible for a certain amount of time. When ear defenders became hard there were leaks and they were uncomfortable.

Mr. J. V. Morris asked whether there was any reduction of dermatitic effects with the newer ones.

Dr. Littler said that there were complaints of irritation with the inserted type of ear defender and that was why the muff and headband type was better. It was very comfortable to wear but there was a tendency for it to get a little hot sometimes because there was no ventilation.

Mr. J. W. Thompson (I.C.I.) said that he knew of some industrial applications where a great part of the energy of the sound lay in the very high frequency range above the band width necessary for the understanding of speech. Could the author say whether there were any ear defenders made specifically to cut out everything, say, above 1 kc/s but which would still allow people to speak to each other?

Dr. Littler said that a defender like a cotton-wool plug would do that. Cotton-wool was useless for low frequencies but fairly efficient for high frequencies. Sometimes very simple ear defenders, such as a little cotton-wool soaked in liquid paraffin, proved very good indeed. He

pointed out that there was no evidence to show that a high-frequency noise band on its own at 4000 c/s and above did any damage on any of the lower frequencies. The chief effect was round about that frequency or a little above.

Dr. O. McGirr (B.O.A.C.), referring to the useful speech range, said that Broadbent had done some work at Cambridge on the differences between consonants.

With regard to ear defenders, he had always given credit for their development to the Canadian National Research Laboratory.

Dr. Littler said that Shaw, the designer of the Safe T muff, was at the Canadian National Research Laboratory, but was previously at Imperial College.

Dr. McGirr said that with regard to the ear defenders it was really a question of utility in relation to expense. The Ferranti Co. had done a lot of work on improving the plastic from which were made epoxy resins. They were very expensive and the risk had to be high before industry could afford anything so expensive.

Dr. Littler said that the headbands of the original ear defenders designed by Shaw were very fragile, but the latest modification was to make them of metal instead of plastic. There had also been trouble due to leakage of the fluid. That had been improved considerably by using better plastic material and better sealing. He had had very little experience of them in use because they were only now being made in large quantities.

With regard to the question about the value of the frequencies for speech, it was very difficult to answer that accurately because all the sounds in speech were of some use on their own but some were of more value than others. We could take the band from 20 c/s to 20,000 c/s as the range of normal hearing for a young person; in saying vowels the vocal chords vibrated at about 100–250 c/s for males and females, and therefore there were all the frequencies from 100 c/s upwards for normal sounds in a series of spectral lines. The spectra were modified by the mouth and pharynx and gave the formants of speech. Vowels required the range 400 c/s–2000 c/s and consonants 700 c/s–3000 c/s to get nearly 100 per cent articulation of all consonants except those like "ch" and "z". In order to get the "ch" sound it was necessary to extend that frequency range to 3500 c/s, and in order to get the "s" and "z" sounds correctly it was necessary to go up to about 8000 c/s. However, even taking only the frequencies from 1000 cycles upwards, it was possible to get the "s" and "z" sounds correctly 45 per cent of the time. There was a middle point at about 1600 c/s where 75 per cent was obtained with frequencies below and 75 per cent with frequencies above. In other words, a great deal of information could be obtained with restricted frequency ranges but, on the whole, good high-frequency reproduction was required for maximum articulation.

Mr. D. W. Vincent (National Institute of Industrial Psychology) asked whether there was any device which the layman could use which would give a rough indication of noise level.

Dr. Littler replied that the only general indication seemed to be that if the noise was such that a person had knowingly to raise his voice, the noise was too intense. If, after a conversation, the voice felt strained then the noise was probably doing some damage during long exchanges. In noisy conditions a person could raise his voice about 30 dB without realizing that he was over-straining it, although he would be aware that he was making an effort to be heard. That particular effect is created sometimes at parties where the noise is loud and people raise their voices; in the end the whole noise level is raised and it becomes distressing.

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PRINCIPLES OF NOISE SUPPRESSION

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Abstract—Noise has many origins, and relief from it may be sought for a variety of reasons. Most problems of noise suppression must be treated individually; but some general principles can be stated. As a first step, the physical characteristics of the noise must be known; the procedure for this is described. Possible methods of suppression are then discussed, including those of sound insulation and absorption, and are illustrated by examples from practice.

INTRODUCTION

Suppression of industrial noise may be sought for a variety of reasons. In the workshop (containing the source of noise) it may be needed to avoid the risk of permanent damage to the hearing mechanism of the personnel employed there, which can arise from prolonged exposure to loud noises, or to give better conditions for the correct hearing of instructions. Excessive noise may also deter potential entrants from seeking employment in the industry and noise reduction may consequently be needed to ensure an adequate recruitment of new labour. Elsewhere in the factory, where the noise may no longer be harmful to the ear, it may be sufficiently loud to interfere seriously with telephone conversations or conferences; and outside, it may be a nuisance in neighbouring residential districts, particularly when work continues throughout the night.

If the noise can be suppressed at the source the reduction is of equal advantage elsewhere within the factory and outside it. This, however, may not always be possible, and the methods which can be applied then depend very much on the situation in which quiet is required.

DESCRIPTION OF NOISE*

In all cases, a first requirement for a systematic approach towards noise suppression is a knowledge of the characteristics of the noise. The physical characteristics are usually expressed in terms of the sound pressure—the small variations of atmospheric pressure which actuate the ear drum and produce the sensation of sound. Because of the wide range of sound pressures to which the ear responds—from less than one thousand-millionth of an atmosphere for the smallest audible sound to about one thousandth of an atmosphere for sounds which begin to produce pain in the ear—it is convenient to express sound pressures on a logarithmic scale instead of a linear scale. This is done by defining the sound pressure level L corresponding to a sound pressure p (dyn/cm^2) as

$$L = 20 \log_{10} (p/0{\cdot}0002) \text{ dB}.$$

The sound pressure level is thus zero for a sound pressure of 0·0002 dyn/cm^2, which is near to the threshold of hearing in the frequency region where the ear is

* For a fuller discussion and details of techniques used for noise measurement see *National Physical Laboratory Notes on Applied Science* No. 10 (1957).

most sensitive; it increases by 6 dB each time the sound pressure is doubled, or by 20 dB for a 10-fold increase. The whole range from the smallest audible sound pressure to the very loud sounds which begin to produce pain in the ear is covered in about 130 dB steps.

Noise is in general very complex and the total sound pressure level alone gives no information about its character. An analysis showing the way in which the sound pressure is distributed over the range of audible frequencies gives much fuller information. For many purposes a comparatively coarse analysis is sufficient, and that normally used determines the sound pressure level in each of a series of bands of frequency, each one octave wide, covering the range of 8 octaves from 37·5 c/s to 9600 c/s. This is the method of describing a noise which is used in most of the examples given later. It is also the method which is coming increasingly into use in proposals for criteria for noise limits, e.g. the damage-risk criterion (ROSENBLITH *et al.*, 1953) or criteria for tolerable noise levels in different circumstances (BERANEK, 1957).

For some purposes finer analysis, which permits the frequency and amplitude of any single-frequency components in the noise to be measured, is desirable, particularly in diagnosing the precise source of a noise. For instance, the source of a single-frequency component in the noise from a machine may be determined through the correspondence of its frequency with that of some operation within the machine, e.g. the contact frequency of gear teeth or the blade passage frequency of a fan. It has also proved useful for deciding which of the many sources of noise in a large factory were mainly responsible for the noise heard at a distance.

Though no single figure can characterize a noise completely, it is often useful to supplement noise analyses by some such figure. For this purpose a figure representing the loudness is perhaps the most satisfactory. Since loudness is a subjective attribute of noise it can only be measured primarily by subjective methods, i.e. by aural comparison with some standard sound, to the sound pressure levels of which a scale of loudness levels is assigned. On the phon scale of loudness level the standard sound is a pure tone of 1000 c/s and its loudness level in phons is defined as being numerically equal to its sound pressure level in decibels. The loudness level of any other noise is then equal to that of the standard sound which, when heard under prescribed conditions, is judged, as the average of the observation of a group of observers, to be equally loud. The scale of phons is thus arbitrarily defined so that it cannot be assumed that there is any simple relation between the number on the scale and the corresponding sensation experienced. An appreciation of the meaning of loudness levels in phons can be gained only by experience.

In order to overcome this disadvantage a second scale has been devised in which the aim is that the scale reading shall be directly proportional to the loudness sensation. The manner in which the scale is divided is determined by experiments in which observers are asked to judge whether one noise is, for example, more or less than twice as loud as another. Naturally there is some diversity of opinion, but the general result obtained is that an increase of loudness level of approximately 10 phons is required to double the loudness sensation. The unit on this scale is the sone, and in order to give precision to the scale it has been agreed internationally that 1 sone shall be defined as the loudness of a sound whose loudness level is 40 phons, and that the scale of sones shall be defined by taking the above relation

exactly. Corresponding values of loudness level in phons and loudness in sones are shown in Table 1.

Subjective measurements of loudness, requiring as they do a group of observers in order to provide a reliable mean result, are suitable only for laboratory investigations. The relation between loudness and the physical characteristics of a noise is, moreover, so complex that it has not proved possible to devise an objective loudness-meter which will give readings in accordance with subjective judgments for a wide variety of noises. Several methods have been proposed for calculating the loudness from a knowledge of the physical characteristics (e.g. an octave band analysis), and though no one of these is completely reliable, this approach gives a simple means of providing a single figure, approximating to the loudness, with which to supplement the physical data provided by the octave band spectrum. The loudness levels given in this paper have been estimated by the method of STEVENS (1956, 1957).

As a guide to the interpretation of loudness levels in phons or loudness in sones in terms of the sensation produced, Table 1 gives values for some common noises.

TABLE 1. LOUDNESS OF COMMON NOISES

Loudness level (phons)	Loudness (sones)	Noise
130	510	Jet engine at 100 yd
120	260	
		Weaving shed
110	130	Loud motor horn at 20 ft
100	64	
		In tube train
90	32	Beside main traffic artery (average level)
80	16	
		City office, windows open
70	8	Conversational speech
60	4	
		Quiet city street at night
50	2	
40	1	
30	0·5	
		Quiet countryside at night
20	0·25	
10	0·12	
		Silence
0	0·06	

SUPPRESSION OF NOISE

(a) *Planning to avoid noise*

Many noises cannot be suppressed at the source without interference with the mechanical process which is being carried out, and in such cases noise suppression becomes essentially the control of noise to prevent it reaching the situation where quiet is required. In any new factory where a noise problem is likely to arise, consideration should be given to the question at an early stage so that measures for noise control can be incorporated in the general plan.

The open plan, where the noisy production operations, the quieter operations of assembly and the still quieter processes of inspection are housed together in one large bay, leads to unnecessary noise for the personnel engaged on the quieter work. Wherever possible the noisy machines should be segregated. It is realized that this may lead to difficulties in arranging the flow of materials, and where overhead cranes are in operation it may be impossible, but there are many cases where it could be applied with advantage.

The location of offices should be chosen with regard to the situation of the main sources of noise, and attention should be given to the degree of sound insulation needed to provide satisfactory conditions, so that this may be embodied in the construction.

In considering the possible nuisance to neighbours of noise escaping from the factory, account must be taken of the more important paths by which noise can escape. Large access doors which may be open for long periods for loading and unloading should be sited on the side where noise is least likely to be a nuisance. Ventilation by open roof lights may have to be avoided, and it may sometimes be desirable to provide a heavier roof than would normally be required, or to introduce a false ceiling to avoid excessive transmission of noise through the roof.

The importance of noise sources situated outside the factory, and in particular on the roof, is sometimes overlooked. Such sources, e.g. fans, Diesel exhausts, compressor intakes, steam discharge pipes, etc., may not be heard within the factory or may be barely noticeable above the main factory noise just outside the building. At a distance, however, they become relatively more important and may be the principal sources of annoyance. Fig. 1 illustrates a case of this kind.

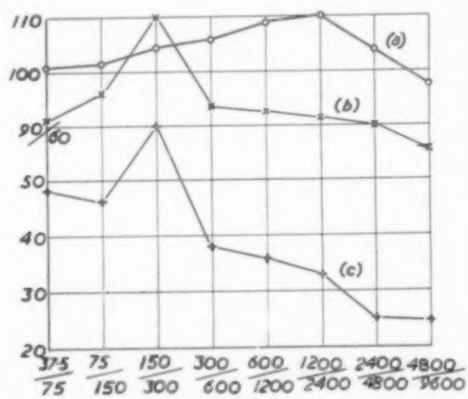

FIG. 1. Noise nuisance from fans on roof of factory. (*a*) Typical noise within the factory; (*b*) noise in fan chamber; (*c*) noise in bedroom of house at ¼ mile distance.

Curve (*a*) shows the noise level in a room containing heavy stamps, and the levels throughout the rest of the factory were much the same. Within the factory the noise of extractor fans situated on the roof was predominant only in the fan chamber itself (Curve *b*), as shown by the high level in the octave band from 150 to 300 c/s. At a distance of about a quarter of a mile the fan noise was the principal component and showed up prominently in the noise analysis (Curve *c*), and at still

greater distances it was readily detectable by ear, to such an extent that in the night hours it constituted a nuisance. Such a noise, in the nature of a steady note (or, as in this case, a note of fluctuating intensity due to several similar fans running slightly out of synchronism), is indeed usually much more readily picked out by the ear from the general background, due for instance to distant traffic or the rustling of trees, than a more nondescript noise of the same loudness, and is consequently more likely to give rise to complaints.

(b) Reduction at the source

The reduction of the noise from a machine is in the main a question for the machine designer and is outside the scope of this paper. There are, however, many noises of quite high level which are encountered in the handling of materials, and more thought and experiment might well be given to their reduction in many factories. Fig. 2 illustrates two such cases. The first (Curve *a*) is the noise from

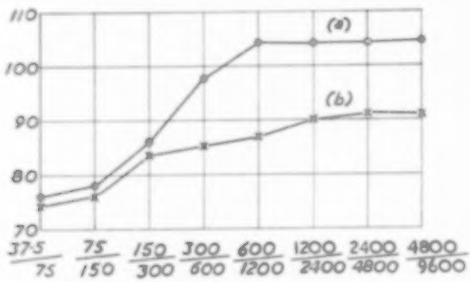

Fig. 2. Noises from handling of materials. (*a*) Metal tubes falling from draw-bench; (*b*) sweeping small castings into metal bin.

metal tubes falling from the draw-bench on to the concrete floor or on to the pile of tubes already produced and awaiting removal. This was one of the major sources of noise in the shop concerned, and it should not be beyond the skill of the engineer to devise some means of catching the tubes, perhaps on resilent guides which would deposit them more gently on the floor. In the second case also (Curve *b*), though the noise is of a considerably lower level, it was almost the only source in the shop. This noise arose from pouring small castings from metal bins on to metal-topped benches, from which, after processing, they were swept back into the bins. It might be considerably reduced by the use of plastic bins and bench tops of plastic or of tough rubber.

Other handling noises encountered have included the fall of small components down metal chutes, with unnecessary weld ridges in them causing the components to bounce, and unnecessary high falls into bins. Again the remedy is to be sought in more careful design and the use of less resonant materials for the chutes.

(c) Sound insulation and sound absorption

Where suppression of the noise at its source is impracticable, the measures which can be taken to reduce it may be broadly classed as sound insulation and sound absorption, which in general must be used in combination. By sound insulation is

meant the prevention of the transmission of sound from one place to another by the interposition of a barrier. It is not necessary for this barrier itself to absorb the sound energy but only to throw it back, though ultimately it must be absorbed. Sound absorption—the dissipation of the sound energy into heat—takes place when panels are made to vibrate under the action of sound, or more effectively when sound can percolate into porous or fibrous materials where the energy is dissipated through friction between the moving air and the walls of the pores.

The sound insulation of a partition is expressed by its sound reduction index, which is the difference between the sound pressure level of the sound incident on the one side and that of the sound transmitted from the other side. Fig. 3, which

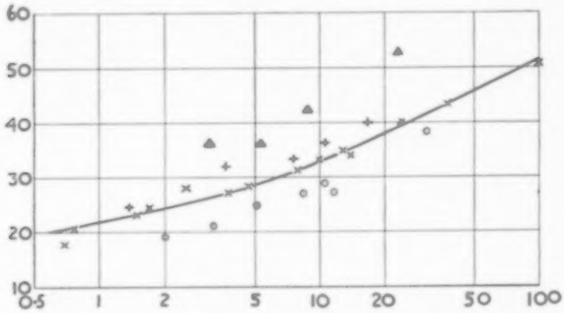

FIG. 3. Mean sound reduction index as a function of superfical weight.
× Single sheets of approximately homogeneous construction.
○ Composite boards of two sheets joined by rigid lattice.
+ Stud partitions.
△ Completely isolated double partitions.

gives examples selected from a large number of partitions tested at the National Physical Laboratory, shows the way in which the average sound reduction index over a range of frequencies (100–3200 c/s) varies with the superficial weight of the panel (ASTON, 1948). The points corresponding to single sheets of approximately homogeneous construction all lie close to the curve drawn. Thus for such partitions the average sound reduction index depends almost entirely on the superficial weight and very little upon the nature of the material. Composite panels, of the general type in which two sheets are bonded together by some form of lattice, are usually worse than a single solid panel of the same weight, as is shown by the points representing this type of construction. Better insulation for a given weight can be obtained from double constructions, provided that there are few ties between the two sheets. Thus stud partitions are shown to be slightly better than single solid panels, and two completely isolated panels can give a considerable improvement.

Fig. 4 illustrates the way in which the sound reduction index may vary with frequency with different types of construction. The four constructions concerned are all of approximately the same superficial weight (about 10 lb/ft^2). On the whole the sound reduction index increases with frequency but there may be large irregularities at high frequencies, and if the noise against which insulation is required is mainly of a single high frequency these must be taken into account. The composite board is worse than the single sheet over the greater part of the frequency range,

but rather better at high frequencies. The stud partition shows an improvement over the single sheet over a larger range of the high frequencies, and the double partition with isolated leaves shows a still greater improvement over a still greater range. At the low frequencies there is little difference between the four panels. Thus for low-frequency insulation weight remains the predominant factor, and neither the nature of the material nor the type of construction has much influence.

The noise reduction which will be achieved by enclosing a source of noise depends not only on the sound insulating value of the walls of the enclosure but also on the

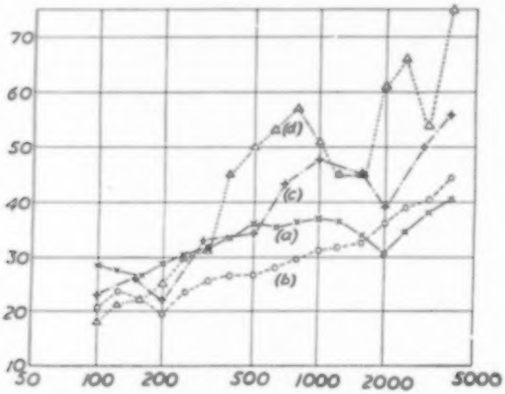

FIG. 4. Sound reduction index as a function of frequency. (*a*) Single sheet; (*b*) composite board; (*c*) stud partition; (*d*) isolated double partition.

degree to which sound is absorbed within the enclosure. With little sound absorption within the enclosure the sound energy produced by the machine builds up, through repeated reflection at the walls, to produce a higher level inside, and consequently a higher level transmitted, than if a large fraction of the sound is absorbed at each reflection. Consequently sound insulating treatments need to be combined with sound absorbing treatments.

The sound absorbing properties of a wall covering are defined by its sound absorption coefficient, which is the ratio of the sound energy absorbed to that incident on it. For noise reduction purposes the most suitable sound absorbing materials are those of a porous nature, for example the various types of mineral wool. Fig. 5 illustrates the way in which the sound absorption coefficient of a mineral wool backed by a rigid wall depends on frequency and on the thickness of the material. Though comparatively thin linings will provide high absorption for high-frequency sounds, large thicknesses are needed to provide good absorption at low frequencies. The figure also shows that the low-frequency absorption of a given thickness of material is improved by providing an air space between it and the backing wall, but that for a given total depth of treatment, the material filling the whole depth is the better. Materials of this nature may be covered with a thin perforated facing for protection without serious loss of efficiency provided the open area of the perforations is greater than about 15 per cent.

Where very high sound insulation is needed, small apertures, cracks at butted joints or gaps below doors must be avoided. A sound reduction index of 40 dB

means that only 1 part in 10^4 of the sound falling on the partition is transmitted through it. An aperture whose area bears the same relation to the total area of the partition (e.g. 3 in^2 in a partition of 200 ft^2) will transmit approximately as much sound as the rest of the partition and reduce its effective insulation by 3 dB. If an aperture, perhaps for ventilation or for the passage of a conveyor belt, is required, the loss of insulation which it would otherwise entail may be reduced by the use of sound attenuating ducts leading to the aperture. This question is dealt with later.

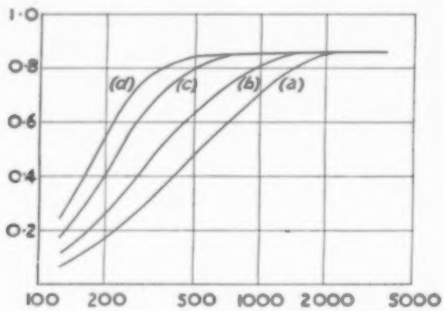

FIG. 5. Effect of thickness and air space on sound absorption coefficients of a mineral wool. (*a*) 1 in. thick. No air space; (*b*) 1 in. thick. 1 in. air space; (*c*) 2 in. thick. No air space. (*d*) 2 in. thick. 2 in. air space.

Where the complete enclosure of the source of noise in a separate cubicle or room is not practicable, consideration should be given to the possibility of partial enclosure by screens immediately around the noise-producing mechanism. Such screens should be as complete as possible and as near as possible to the source of noise, and should be lined on the inside with sound absorbing material. In some cases they might well take the place of safety guards already existing.

Less effective, though still worth while, are absorbent cowls immediately above the site of a noisy operation, which can reduce to some extent the noise which spreads to the rest of the shop. Where the sources of noise are distributed throughout the whole shop, a general absorptive treatment on the ceiling is advantageous except perhaps for very large shops with high ceilings, when the effect is the least and may not be justified economically. The precise value of such a treatment is difficult to assess. As with an absorbent cowl, it does not reduce the noise coming directly to the operator from his own machine. It reduces the noise reaching him from more distant machines, and the general level of reverberant noise throughout the shop. The extent of this reduction depends on the degree of sound absorption previously existing, but usually it will not exceed about 6 dB, and the reduction at the ear of an operator close to a machine may be less than this. The resulting clarification of the noise from his own machine may, however, be of some subjective benefit to the operator.

(*d*) *Anti-vibration mountings*

In addition to the noise which it produces in the air, a machine may transmit vibration through its foundation to the building structure. Such vibration can be

transmitted through the structure with little attenuation and produce noise in distant rooms which would otherwise be quiet. To suppress such noise, the machines must be mounted on resilient supports, of which many proprietary types are available. It is essential, however, that the characteristics of the mountings used should be chosen correctly in relation to the mass of the machine and the frequency of the vibration which it produces. Incorrect choice may indeed lead to more vibration being transmitted to the structure than would have been the case if the machine had been rigidly bolted down. The requirement is that the natural frequency of the machine on its resilient supports must be much lower than the frequency of the vibration it produces. This necessarily entails that the machine as a whole can vibrate, and any connexions to it must be sufficiently flexible to take up this vibration. If a machine and its driving motor are independently mounted, for instance, the drive must be flexible. In the case of a light machine the amplitude of its vibration can be reduced by mounting it rigidly on a heavy block which is itself flexibly mounted.

(*e*) *Sound attenuating ducts*

It has already been remarked that the loss of insulation caused by an aperture in a sound insulating construction can be reduced by the provision of a sound attenuating duct leading to it. Sound attenuation may also be needed in the ducts of ventilating systems to prevent the noise produced by the fan reaching rooms, and similar ducts on the external side may sometimes be needed where fan noise produces a nuisance outside the building. The principle used is to split the duct into a number of narrow rectangular channels by panels of sound absorbing material. The noise reduction in decibels is directly proportional to the length of such a duct, and the way in which it depends on the width of the channels and the thickness of the absorbent splitter panels is illustrated by the curves of Fig. 6. These have been calculated from theory (Morse, 1939; Cremer, 1953) and measured values of the appropriate acoustical characteristics of a particular mineral wool. In general the attenuation increases with frequency to a maximum near to the frequency for which the wavelength of sound is equal to the channel width. At frequencies above this maximum the attenuation can be increased by introducing bends into the duct, but such bends have little or no effect at lower frequencies. Curves (*a*) show that decreasing the channel width while keeping the thickness of the absorbent splitters constant increases the attenuation at all frequencies. At low frequencies the attenuation is approximately inversely proportional to the channel width. Curves (*b*) show that increasing the thickness of the splitters, keeping the channel width constant, increases the attenuation below the maximum but has little effect above. Over part of the low-frequency range the attenuation rises more rapidly than in direct proportion to the splitter thickness. Consequently, if the ratio of splitter thickness to channel width is kept constant (preserving the same free cross-sectional area in the duct), the low-frequency attenuation is increased when the splitter thickness is increased, but at the expense of the high-frequency attenuation. This is illustrated by Curves (*c*). The most appropriate design of sound attenuating duct thus depends upon the frequency spectrum of the noise to be reduced and the reduction needed, as well as on the space available for the treatment.

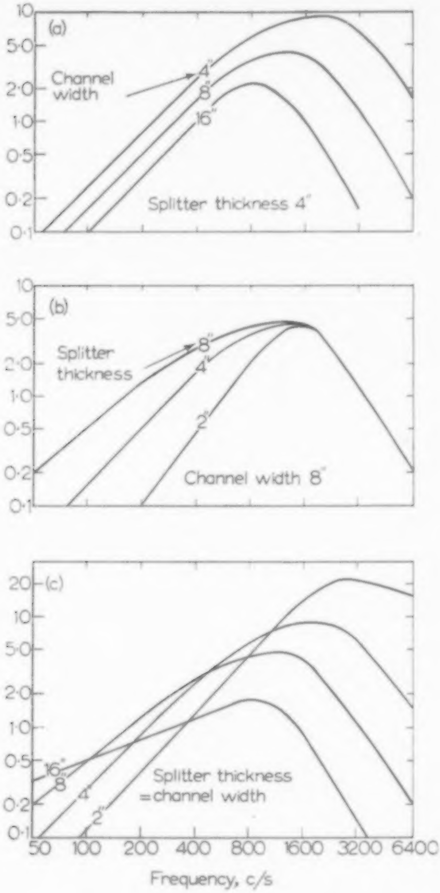

FIG. 6. Attenuation of sound in ducts. (*a*) Variation with channel width at constant splitter thickness; (*b*) variation with splitter thickness at constant channel width; (*c*) variation with splitter thickness and channel width at a constant ratio of the two.

(*f*) *Low-frequency pulsations*

It has been observed that low-frequency noises are the most difficult to suppress, whether by sound insulation, sound absorption or by attenuating ducts. Low-frequency pulsations, usually produced by a pulsating gas flow, are often a source of serious annoyance, however, and other methods for their suppression must be sought. These will usually take the form of some type of expansion, baffle, or resonant silencer to smooth out the gas flow. The problem is not always amenable to a simple solution, and the treatment which can be employed is often dictated by factors peculiar to the plant or machinery concerned. Sometimes the best solution acoustically is impracticable because space is not available for the silencer needed, or it cannot be fitted at the appropriate place in the system—points which could perhaps have been covered in the planning stage. In general the problem is eased when the noise consists of a nearly pure tone or a series of harmonic tones based

upon a fundamental which remains sensibly constant, e.g. the noise from the intake of large slow-running air compressors, or from the exhaust of large Diesel engines used, for instance, to drive electric generators.

Attenuation of the low frequencies may be obviously desirable because the noise is too loud or because of readily apparent vibration set up in associated pipework, etc. On the other hand the sound may be inaudible or nearly so by reason of its low frequency, but still have a very high sound pressure level which, radiated from the end of a duct or chimney stack and transmitted through the air, can cause marked rattling of doors, windows, and other lightweight structures at a distance —effects often wrongly attributed to ground-borne vibration. An example of this is shown in Fig. 7, which gives the low-frequency end of a narrow band analysis

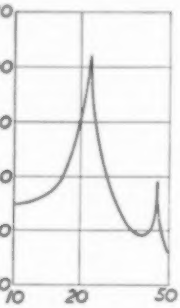

FIG. 7. Low-frequency noise from Diesel exhaust system at 50 yd from exhaust stack.

of the noise from a Diesel exhaust system, measured on the balcony of a block of flats some 50 yd from a tall chimney stack through which the Diesel exhaust was ultimately discharged. An efficient audio-frequency silencer (absorbent lined) had adequately reduced the audible noise so that the loudness even at the stack top was very low. Accordingly the stack had been dismissed as the cause of the vibration effects complained of by the flat occupants, and ground-borne vibration from the engine itself was suspected. The measurements showed clearly that the audio-frequency silencer had failed to remove the large subsonic component of the airborne noise in the Diesel exhaust, and that an efficient low-frequency silencer was also needed, whereas the introduction of ground breaks, which had been suggested, would have been completely ineffective (and costly). The moral here is that when very low frequencies are concerned, the ear is a bad diagnostic instrument and objective measurements should be made.

An example of the use of two silencers, one for low frequencies and the other for higher-frequency noise, is shown in Fig. 8, which relates to the noise measured 1 ft away from an 18 in. diameter asbestos cement pipe conducting air from large blowers to sewage aerating tanks. The pipe totalled some 300 yd in length and emitted a tinny rattling sound, resulting in complaints from neighbouring houses, particularly of the noise during the night. The fundamental frequency of the blowers was 13·5 c/s and resulted in large vibration effects at bends in the pipe. Narrow band analysis showed harmonics of this tone up to 2000 c/s or so. An

expansion chamber of 50 ft^3 (some 15 times the volume flow per stroke) and an absorbent type silencer were fitted in tandem in the pipe close to the blowers, resulting in complete eradication of noise and vibration—the measured residual noise shown being due to background noise from the remainder of the site.

The use of a resonant low-frequency silencing system is illustrated by Fig. 9. This shows the sound pressure levels measured near the intake of a large double-acting air compressor running at about 6·25 rev/sec, thus producing a series of

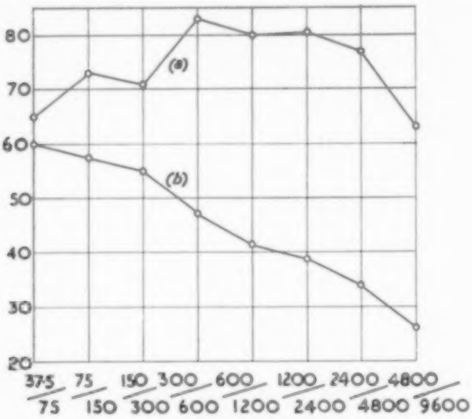

Fig. 8

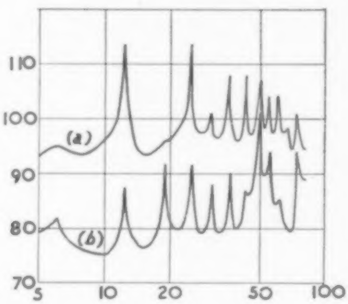

Fig. 9

FIG. 8. Noise from air supply pipes to sewage aerating tanks. (*a*) Before treatment; (*b*) after treatment.

FIG. 9. Noise from intake of air compressor. (*a*) Before treatment; (*b*) after treatment.

harmonic tones based on a fundamental of 12·5 c/s. A secondary series of such tones with a fundamental of 6·25 c/s due to asymmetry in the double action is also apparent. The large component at 12·5 c/s produced rattling of doors and windows at a distance of 200–300 yd. At the intake on the roof it was readily observed that the flow was not entirely inwards, but that the pulsations produced a cyclic reversal of flow of large amplitude. This was apparently due to the length of the intake pipe being such as to resonate to the 12·5 c/s component (and odd multiples of it), producing amplification of the alternating components of the flow at the frequencies concerned—an effect which might be avoided in some cases by a proper choice of the length of the intake pipe. This component was reduced by about 25 dB by fitting a closed side branch to the main intake pipe near the compressor itself. The length of the side branch was about 22 ft, equal to a quarter wavelength at 12·5 c/s, and therefore resonant to this frequency. Such a quarter-wave pipe attenuates also the odd harmonics of the fundamental to which it is tuned. In addition a perforated plate was fitted between the end of the main intake pipe and its air filter to increase the acoustic resistance at the open end and give attenuation of the higher harmonics, with the final results shown by the Curve (*b*).

Acknowledgments—The work described above was carried out as part of the research programme of the National Physical Laboratory, and this paper is published by permission of the Director of the Laboratory.

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DISCUSSION

Mr. I. HUGHES asked whether, having made noise intensity measurements in a certain location, it was possible to predict reasonably accurately what noise reduction would be obtained by putting a certain shielding round the source of noise.

Mr. FLEMING said that it was usually possible to predict but not always, because a type of shielding might be used about which nothing was known.

Mr. H. J. PURKIS (Building Research Station) said that he would like to confirm all that the author had said about the possibility of taking measures to reduce noise in buildings both in relation to the noise inside the buildings and in relation to the noise coming from buildings, which affected local residents in industrial areas. At the Building Research Station they had made measurements in three or four factories which had subsequently been treated in order to reduce noise. As had been said, the problem was essentially one which should be tackled at the design stage because at a later stage probably the only thing which could be done was to put in absorbent material. Insulating measures were impracticable once a factory had been designed. Measurements had been made in several factories in which the maximum amount of absorbent treatment had been done and the reduction in sound levels was comparatively small, being only about 6 dB. In fact, in most of the cases where measurements had been taken, the reduction had been even less than that, something like 3 dB for quite a considerable amount of absorbent.

In one particular steel works it had not been possible to introduce very much absorbent material but it had proved possible to introduce baffles between the spaces where the majority of the noise was and the places where work was carried on. The reduction there was quite considerable, being about 10 dB, in the high frequencies in particular. It might well be that even if absorbent material could not be introduced, the use of insulating baffles might be a good thing in order to reduce noise in large enclosures. He would repeat, however, that the greatest good could be done at the planning stage in order to isolate those parts of the factory which were liable to be noisy.

Dr. ROGAN said that they had been told that noise should not be measured in terms of decibels, but the author of the paper had done so, and so had other speakers.

Mr. FLEMING said that he was sorry if he had given that impression. The physical magnitude of noise should be measured in decibels. What they measured was the sound pressure, and they expressed it in decibels. He had said that it was often very useful to supplement the measurement of a physical characteristic by an assessment of the loudness, and that was expressed on one of two scales, either in phons or in sones.

Mr. J. A. ADAM (United Steel Companies Ltd.) said that they had been told that the damage to the ear was taken in relation to time as well, so that an assessment of noise should be made in terms of some sound measurement in time such as dB/hr. That would be very difficult to log. He wondered which was the best unit on which to make an assessment.

Mr. FLEMING said that he did not know whether there was sufficient evidence on which to say which was the best way of doing that. In the American Air Force they had laid down some regulations in connexion with damage-risk criteria and they had said there that the energy of the noise should be integrated over the time of exposure. A person could be subjected to, say, 80 dB for 10 hr a day, but if he was only subjected to noise for 1 hr a

day it could have 10 times the energy, which would be 10 dB more. If the person was only subjected to it for 6 min per day it could be 10 times as much again, which would be 100 dB, and if he was subjected to it for only 36 sec it could again be 10 times as much which would be 110 dB.

Dr. O. McGirr (B.O.A.C.) said that the United States Air Force provisions were not nearly as complicated as they sounded. They constituted the best study he had seen with a view to introducing preventive measures.

He would like to ask a question about the absorptive properties of things such as fibre-glass and other materials. Was there not a saturation point reached with those materials in absorbing sound energy so that gradually their effectiveness wore off? He understood that the effect deteriorated with the continued absorption of sound.

Mr. Fleming said that he had never come across that idea before. All that happened was that the air vibrated in the pores and the motion was dissipated into heat so that the fibre-glass warmed up. He had no precise data in mind but he believed it had once been estimated that the noise produced by a football crowd all cheering together for a whole game would only produce enough energy to make one cup of tea, so that the amount of heat produced was very small. The energy in sound was very, very small indeed. In a progressive sound wave in which the sound pressure level is 130 dB the power transmitted is approximately 1 W/ft^2 of the wave front.

Fibrous materials with brittle fibres, covered with a perforated sheet, might deteriorate in time through breaking-up of the fibres under the vibration of the cover sheet induced by intense sound.

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THE EFFECTS OF NOISE ON WORK

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INTRODUCTION

It is appropriate that the question which I am going to discuss during the next 40 minutes or so should come at the end of this Conference, because it is really a fundamental question about noise. It is also a very nebulous one which is proving extremely difficult to answer. It is probably true to say that many people feel that they know the answer to it and assume that, in general, noise is a bad thing. Certainly the large amount of work which has gone into the physics, the measurement, and reduction of noise in various circumstances, is based on the assumption that noise is in some respect or other harmful and to be avoided wherever possible.

We have already heard of the physical damage which very loud sounds can do to hearing, and we also know that noise, in many forms, can be an annoyance and have all manner of undesirable effects on some people. But we also want to know whether noise, which is not loud enough to produce physical damage and which as far as can be seen is not producing any particular annoyance, can yet produce some form or other of interference with mental work.

We want to know how important this sort of noise is and whether it has any upsetting effect on normal human beings engaged in ordinary everyday activity, or in industry. In particular we want factual evidence, if possible in numerical form, about whether some upper limit of intensity, or some form of spectral distribution, can be quoted beyond which harmful effects occur on performance.

It is very fortunate that, as I said, many people have felt that they knew the answer, that surely noise must be upsetting in some way or another, because experimental work on human performance is not as straightforward as may appear at first sight. In fact, work has continued on the subject since the early 1930's or even since the first world war, and while the physical and physiological aspects of the subject have progressed, as we have heard, nevertheless results on the output of people working in noisy conditions have, until very recently, been either negative or confusing.

AN INDUSTRIAL RESULT

There is one experiment done a long time ago which, without much room for doubt, showed that noise could interfere with industrial output; this should be mentioned straight away because its result has not been improved upon in its own sphere, or disproved. It was in 1932 that Weston and Adams, working with the support of the Medical Research Council published the first results of an experiment carried out in a weaving shed where the general noise level was given as 96 dB. A group of ten weavers were provided with ear plugs which were said to reduce the noise transmitted by from 10 to 15 dB. This group wore the plugs on alternate weeks for a period of 6 months and individual records were kept for this time. It appears that all ten weavers produced a greater output during the weeks

when they wore the plugs than during those when they did not. The difference was small, being only 1 per cent, but it was consistent and applied to all ten weavers. The same workers continued the experiment with further groups of subjects and confirmed this result.

It was noticed, however, that some of the workers who used ear plugs did not like them and thought that they did not help much at all. This illustrates one of the many difficulties which work on human performance presents, namely, that subjective judgments are unreliable when compared with what we are able to count or measure. This distinguishes the type of experimental work which we at the Applied Psychology Unit try to do and which has rapidly increased in America in recent years, from what many people consider to be psychology, namely, what people think and feel.

ANNOYANCE

Perhaps the most general reaction to noise is that of annoyance, and it might be thought that the best way to study the effect of noise on human beings would be to look for this annoyance and to look for the effects on emotions which annoyance causes. Professor BARTLETT in 1934 defined noise as "any sound which is treated as a nuisance". In spite of all our progress in measurement it is still very difficult to improve on that statement. Of course, it does not refer particularly to industrial, high intensity, comparatively meaningless noise so much as to noise in everyday life. It reminds one, however, that, for example, the proof reader working in a printing concern in a quiet room where the average noise level may be 60 to 70 dB is just as liable to interruption and annoyance by noises as are the workers in the Monotype caster room where the noise level is 95 dB.

The trouble is that nuisance, or annoyance, is a very individual matter influenced by personality, general mental health and day-to-day mood changes. It can be dealt with either clinically, taking every case and every person separately, or in an overall statistical way, in which case these individual variations make it very laborious and uncertain to extract general principles. Therefore, we who call ourselves experimental psychologists leave this approach to social psychologists, public opinion surveyors and works medical officers, and concentrate instead on what can be objectively observed or measured about a man's behaviour or work or output. This does not mean that we regard annoyance or other emotional phenomena as unimportant; but only that we realize that we do not yet know enough about the working of the human being to be able to treat these matters generally.

THE EXPERIMENTAL APPROACH

The type of noise situation which is probably the most important in practice in industry is that of a steady, often moderately intense and comparatively meaningless background of familiar noise in which people are carrying out familiar and well-learned jobs. From the point of view of the experimenter this is the easiest and most satisfactory type of situation with which to work. Meaningless noise is the easiest type to produce; a well-practised task avoids a lot of technical difficulty arising from a gradual but sometimes sporadic improvement in proficiency. Yet this situation is also likely to be a barren one in terms of positive results. We will have, in fact, carefully excluded a number of circumstances which the work of the last two decades has shown to produce measurable changes of output on experimental tasks.

(1) Noise which has meaning is known to be more distracting than meaningless sound, especially if the meaning is a little elusive; if, for example, it is speech which is only partly heard or if the sound seems to be localized but the source is somewhat ambiguous and cannot be placed without some thought or effort.

(2) Noise which is intermittent, especially if its onset is unexpected, is known to be disturbing. There are some very old experiments on this point, as, for example, those of Morgan in 1916, who used an "assortment of bells, buzzers and other noise-makers". The subject was doing an involved task of letter coding and it was found that there was an appreciable slowing down in performance every time the noises were turned on, and then again each time they were turned off, with a return to a normal speed of working between times.

(3) When a task is not very familiar or very well practised, one would expect a given noise to be more disturbing than if the task were well known. There does not appear to be any direct experimental evidence for this, but it is a reasonable hypothesis which is supported by the opinions of people working on the subject. Most tasks, when they are fresh and unpractised, require attention to a comparatively wide range of features. In approaching a new situation one is more ready to accept any fresh stimulus as possibly belonging to the situation. On the other hand, with a task which is well known we know what signals to expect from it and in what direction attention is necessary. Thus, any irrelevant underlying noise would be less likely to interfere.

If we exclude meaning and variability from our noise and consider only tasks which are well practised, we are deliberately taking the type of situation where a noise will be least disturbing. Conversely, of course, if we do find an effect of noise in this type of situation the result will be more useful and less open to criticism.

SOME EXPERIMENTS

So at last I come to some experiments which have recently been done by Broadbent of the Applied Psychology Unit. Some of you may have heard a broadcast made by him a few months ago in the "Science Survey" series in which he spoke of his hypothesis of "mental blinks" which he developed to account for his results. We shall come to that later, but first I want to consider how he arranged the experiments and what the results were.

The room in which these experiments were done was an inverted tank 16 ft square and 8 ft high, in the walls of which large horn loaded loudspeakers were mounted. These were supplied, through substantial amplifiers, from a magnetic tape record of machinery noise. The record was of some rather amorphous machinery noise of a general character. It was indefinite in the sense that no particular component was prominent and that the noise was meaningless. The energy content of the noise was equally distributed over the octaves from 40 to above 5000 c/s. For the "noise" condition the noise level was adjusted to an intensity of 100 dB, and for the comparatively "quiet" condition to 70 dB.

The subjects performed their tasks one at a time in this room, the experimenter remaining outside but keeping watch on the subject through an opening. This isolation, which was carried to the extent of depriving the subject of his watch and cigarettes, was a necessary part of the tasks. The first two tasks were of the type

of experimental tasks which we call vigilance tasks, and they are known as the "Twenty Dials Task" and the "Twenty Lights Task".

THE TWENTY DIALS TASK

In the twenty dials task there were twenty steam pressure gauge faces 6 in. in diameter distributed on three sides of a 12 ft square with the subject seated in the centre. The pointers on these gauge faces were normally stationary and each indicated rather below a "danger mark". From time to time one of these pointers would move until it showed a reading above the danger mark, and when it did so the subject had to restore it to its proper reading by moving a knob below the dial. The time taken between the pointer movement and the turning of the knob was the experimental score. This watch-keeping lasted for $1\frac{1}{2}$ hr and in this time there were fifteen signals, and the time between signals varied from 1 to 12 min. There were a few signals which were "seen" in the sense that the subject was looking at the dial when its pointer moved. This proportion showed no effect of noise. The remaining signals were "found", and of these the proportion found in less than 9 sec, called "quick-founds", is the score of interest.

Ten subjects took part in the experiment, each on 5 days. The first 2 days were "quiet", days 3 and 4 had "noise", and the fifth day was again "quiet". It was found that, taking all the subjects together, the proportion of signals which were "quick-found" was reliably lower on the noise days, days 3 and 4, than on any of the quiet days.

THE TWENTY LIGHTS TASK

The twenty lights task was very similar to this except that the dials were replaced by under-run motor-car headlamp bulbs which were covered with paper so that they gave a dim glow. This was done so that the turning on of a lamp would not immediately attract the subject's attention if he were looking the other way, yet would be clearly distinguishable if he were looking at it. The response in this case was pressure on a response key. There were two groups of ten subjects and they each took the test five times. The first group had noise conditions on days 3 and 4 and second group on days 1 and 2.

Again the score was the proportion of signals which were "quick-found", but in this case when all the subjects' results were added together there was no difference between the noise and the quiet condition. It was also found, however, that on this experiment there was no overall improvement with practice from day to day, while in the case of the dials there had been such an improvement. This suggested that there might be a relation between whether an individual subject showed an improvement with practice and the presence of an effect of noise.

INDIVIDUAL DIFFERENCES

Consequently, the first group, who were treated in the same way as in the dials test, were divided into two sub-groups of five according to whether practice gave some improvement or some deterioration. In the first sub-group, whose scores were appreciably better than those of the second, it was found that the results in the noise condition were appreciably less good than in the quiet condition. It was also possible to obtain a correlation between the individual scores of practice improvement and noise effect which was statistically reliable.

This experiment illustrates the advantage of not being satisfied with an overall score but of analysing the score into parts in whatever ways are possible and whatever ways appear to show promise.

TIME EFFECTS

One way of breaking down an overall score, which has been very helpful on other occasions, is to look for a steady shift in performance as the test proceeds, by taking successive periods throughout the test and scoring them separately. Depending on circumstances we may find an improvement in score, which we call "practice", or, of course, performance may decline, in which case we call it "fatigue". Nowadays the word "fatigue" is always used in inverted commas.

A disadvantage, however, with a task such as this is that the score for, say, a half-hour's work tends not to contain enough items to enable reliable conclusions to be drawn, and such tends to be the case here. The scores for each of the three half-hours of each experimental period suggest that there is a drop in output from one half-hour to the next and that this drop is greater when the noise is present than when it is absent; yet the data are not reliable enough to show this without doubt. However, there is also a shift from one experimental run to the next, and we can take the two runs which follow each other in the same noise condition and subtract the first quiet day's score from the second and the first noise day's score from the second noise day. We then find that the difference between the "noise" days is greater than that between the "quiet" days, and that this difference is reliable. Thus we can say that performance in noise becomes worse relative to that in quiet, with increasing length of exposure. This is reliable statistically. More colloquially, we can say that in noise people "fatigue", in this task more quickly

DETAILED SCORING

Those are two examples of the value of analysing the overall score into various components, and here are two more. If we count the longest succession of signals which receive no response with 9 sec, we find longer series in the second noise run than in the second quiet run. Notice that the difference is in the second run and not in the first. The average values were losses of four signals at a time in noise and only three in quiet.

Again, if we divided the lights into those directly in front of the subject and those to one or other side, we find that those in front were less quickly seen, which is rather unexpected. If we only count these, which were in front of the subject, we find a small but statistically reliable difference in favour of the quiet condition compared with the noise condition.

Therefore, in this experiment, although there was no reliable difference in overall score in the noise and quiet conditions, yet we find that there appear to be changes in detail. We have found differences in the individual subject's reaction to the noise, which is not in the least surprising, although we often hear of experiments being done with only two or three subjects on the assumption that their results will apply to every one else. We have found differences in both the spatial and the temporal pattern of response which require further investigation. In his third experiment BROADBENT looked particularly into the question of the temporal pattern and for this he used a different type of experimental task, namely, a five-choice serial reaction task.

THE SERIAL REACTION TASK

To digress for a minute, the ordinary measure of reaction time is one of many short tasks which have been explored by previous workers without any effect of noise being found. In fact, early experimental psychologists used this measure very widely, looking for an effect from all manner of interfering circumstances such as loss of sleep, high temperatures, or prolonged periods of fatiguing work such as that of driving heavy long-distance lorries throughout the night. Always it was found that, faced with a short test, the subjects would pull themselves together for the necessary few minutes and score a normal result.

In this experiment the subjects' task differs from the simple reaction time task in three important respects. First, it is a choice situation. At any moment during the experiment the next stimulus to appear can be one of four possibilities which have an equal probability of appearing. The subject has to select the appropriate response from four possibilities. This brings in the possibility of error or incorrect choice which can be counted as a score. It also requires, in popular language, a certain amount of thought.

Second, the task is continued for a considerable time and the subject is to a certain extent working against time. Thus, whatever particular effort the subject might make to begin with has a good chance of wearing off. Preliminary experiments were continued for 1½ hr, but these tests showed that after all only half an hour was necessary to obtain results of interest.

Third, the score used is not merely an average time taken to make a response. This was indirectly measured by counting the number of responses the subject made in a given total time; but much more interest was found in the subjects' mistakes and in their manner of making them.

The subject's task in this third experiment was arranged like this. He sat facing an inclined panel, like a desk, on which were five brass contact discs spaced at the corners of a pentagon. Beside each disc was a small neon signal lamp. As each lamp was lit up he had to touch the corresponding contact disc with a stylus and this contact caused the lamp to be extinguished and the next, one of the remaining four, to come on. At the same time a "correct response" was recorded on a counter. If the subject touched the wrong disc the display still changed, but in this case another counter scored a unit of error. If the subject made no response for a period of 1½ sec, this fact also was recorded as a "gap" in performance on a third counter.

I think in this experiment the average rate was about two per second, so that a 1½ sec gap was a considerable pause. Counters used like this, of course, give one an overall score in which there is no record of the individual reactions, and we have already noticed that overall scores are less likely to be interesting than detailed scores. Nevertheless this arrangement is a reasonable compromise, for not only do we have the "error" and "gap" scores but also the group of counters can be photographed whenever desired and by subtraction a series of scores can be obtained showing how the subjects' performance changed with time.

The conditions of noise in this experiment were similar to those of the previous two, being 100 dB in the "noise" condition and 70 dB in the "quiet" condition. There were eighteen subjects in the experiment, and each had two half-hour periods of test. With nine subjects the noise condition came first, and with the other nine the

first run was in the quiet condition. They were instructed to work as rapidly and accurately as possible for half an hour.

The count of correct responses showed, as was more or less expected, that noise had no effect. There was little difference with time during each run, although there was at first a slight improvement followed by some loss.

The counts of gaps and of errors showed a rather instructive relationship. At first there was little increase in errors with time, but an appreciable increase in gaps with time. In the second run this position was reversed, and it appeared that gaps had been replaced by errors. The reason for this was not difficult to find, and is that the hand movements involved are simple and fairly quickly become well learned, and when that has happened there is a tendency to continue a regular movement of the hand even though attention has strayed, giving a wrong response. In the earlier stages of learning such an interruption of attention causes the hand movement to be interrupted or, more correctly, causes the individual hand movements to wait for instruction from whatever higher nervous centre is doing the selecting, and leads to a "gap" being recorded. Consequently, in giving the effect of noise, only one score, the "error" count, is given.

Taking the whole group of subjects, the average number of errors made per subject in the noise condition was 57, compared with 37 in the quiet condition. This is an appreciable and reliable increase, but in the whole experiment the overall proportion of errors was only 3·7 per cent, so it is not surprising that the overall count of correct responses showed no effect. Noise appears in fact to have influenced performance only in some detail, in the liability to occasional error, which in some practical circumstances might be a very important detail.

TIME EFFECTS

The other conclusion from this experiment is that the effect of noise did not appear in the first few minutes of the test. When five separate 5 min periods were taken, the first of these periods showed no difference between noise and quiet; the noise condition only showed more errors in the later 5 min periods. Thus if the test had been a short test lasting 5 min or less, no noise effect would have been found; and this confirms the suggestion from the first two experiments that the effect of noise is to increase the fatiguing effect of continued work.

In the final part of this experiment Broadbent took another fourteen subjects and did the experiment again, with the difference that an attempt was made to suggest to the subjects that noise would improve their performance. They were seen individually and given details of this supposed improvement, and were shown graphs prepared for the purpose. In spite of this instruction they also made more mistakes in the noise condition than in the quiet, the figures being an average of 35 errors in the noise and 24 in the quiet. The increase was in the same proportion as before, so that although the instructions might be responsible for an improvement in their results, on the whole it made no difference to the noise effect.

Clearly, then, we can say from these three experiments that meaningless noise of 100 dB intensity does have an effect on performance but only in some detailed respects, and we shall consider some possible reasons for this shortly.

MOTIVATION

First, however, there is a point I want to make about motivation. This is a point which is raised by the second part of the third experiment. Motivation is a difficult subject to introduce in experiments of this kind, and it is even a difficult word to define properly. Nevertheless, even if the word is not mentioned in an experimental report, there are implied assumptions about it. The most usual state of affairs is that the experimental subjects are research workers or students, and although it is usual, wherever possible, not to tell the subject what the experiment is about, nevertheless the subjects are people who take a serious view of the importance of research in general and can be relied upon really to try to do their best and to concentrate on the task in hand. More than this, it is known that students and research workers who are people of reasonable academic attainment tend to be comparatively resistant to fatigue effects and are less likely to be upset by noise than the average for the population. They have the ability to concentrate.

In these experiments, however, the subjects were not so selected. They were all young Servicemen of no more than average attainment and, furthermore, they had no particular interest in research in general or in the effect of noise in particular. Their motivation is probably very like that of most industrial workers. They were just doing a job of work. Perhaps it had some slight novelty value, but they were mainly constrained to try to do it well by such matters as personal relationship with the experimenter, self-respect and such-like matters which cannot be properly defined, still less measured.

For this last group of subjects, however, the preliminary attempt to suggest that noise had a stimulating effect would be calculated to give them a greater interest in the work as a whole. In fact, their overall score of errors was less than for the group of "unencouraged" subjects, although the relative effect of the noise was just as great.

Too much stress must not be laid on this point, however, but we can say with confidence that in spite of the suggestion that noise would help them the last group of subjects still made reliably more mistakes in the noise than in the quiet condition.

THE MECHANISM OF THE EFFECT OF NOISE

Now we have to consider how a noise can interfere with performance. It was stated earlier that these experiments would be concerned with familiar noise and its effect upon familiar tasks. First, the subjects were all used to working in this type of noise, of this order of intensity, and the noise was of no particular character or meaning, so it is reasonable to claim that the first condition was fulfilled.

On the other hand, it is necessary in laboratory experiments to use artificial tasks which will concentrate on some particular type of performance or skill and will enable us to measure the results in various ways. To fulfil this second condition it is therefore necessary either to give the subjects practice on their tasks before the experiment starts or to use tasks where we know that practice is not very important, and to arrange the experiment in such a way that if any steady change in output with time occurs we can find it.

In these experiments the last method was used. It is known that learning occurs primarily in the control of movement or the analysis of complicated sensory inputs.

Therefore, by making the experimental stimuli as simple and unambiguous as possible, and the necessary response as elementary as possible, the effect of practice is minimized. Even so, as we noticed earlier, the exchange of gaps for errors in the serial choice test was probably due to the effect of learning on even this simple pattern of muscular movements.

The fact that noise made no measurable difference to the overall output score in the third experiment, and in many experiments in the past which used some measure of overall performance, is not at all surprising when we consider how very adaptable the human animal is. In the field of physiology we find, for example, that circulating blood is maintained within a very narrow range of acidity in spite of wide changes in type of food or in the production of carbon dioxide during exercise. Again, body temperature is only changed slightly by large changes in environmental temperature or by increased production of heat in exercise.

SELF-REGULATING SYSTEMS

In both these examples there are effective regulating mechanisms which tend to maintain the same output quantity in spite of disturbing influences. In fashionable language, they are "feed-back mechanisms". Another example in which the analogy with physical servo systems is more obvious is, of course, that of the maintenance of arterial blood pressure by direct nervous reflexes such as that from the carotid sinus.

When such a system is operating it becomes very inefficient to try to study the effect of varying some input quantity by looking for a change in output. Depending on the kind of system, we have to look instead for some indirect measure of the behaviour of the system, looking perhaps either for the error signal, the signal which is fed back as a monitor of the output, or for some aspect of the behaviour of the system which does not appear to be subject to the regulating influence of the system.

I hope that that analogy illustrates the need, in looking for an effect of noise on the behaviour of human beings, to use some such indirect measure and not to be surprised if the total output appears to be unchanged or changed by some small amount which is hidden by other sources of variation or which is statistically unreliable.

In fact, in recent years various experimenters have been looking for disturbances in performance resulting from various different kinds of environmental stress such as deprivation of sleep or high atmospheric temperatures, and in every case if what the subject was told to do and therefore, presumably, was trying to do was measured as a gross score the stress appeared to have no effect, or the effect was small and variable.

There are two ways which have so far been used to avoid this difficulty. In the first, which may, in servo system language, be compared with looking for the error signal, it is supposed that when a subject is able to maintain his output in the presence of some stress he does so at a greater cost to himself in terms of effort or energy expended. Therefore attempts are made, for example, to estimate muscular tone in muscles not directly involved in the task, or the rate of eye blinks is counted.

The second way is illustrated in Broadbent's experiments, and it is that of looking for changes in the way the experimental tasks are carried out or for aspects

of the subjects' performance which are to some extent distinct from their goal or target. In the first and second experiments the subject was looking for rare signals, and whenever he saw one he made the appropriate response. The change that noise brought about was that some signals were not noticed as quickly as they were in quiet conditions. Noise has no effect upon eyesight or on speed of response and therefore the change must be one of attention.

In the third experiment the subject was steadily working away at his choice task and turning out a large number of right responses, about the same number in the noise as in the quiet condition, but from time to time there was an interruption in the smooth flow. At first there were distinct breaks and later there were errors. These gaps or errors were very few in the first few minutes of work but they became more frequent as time passed, and the increase with time was more rapid in the condition of noise.

These results fit well into a hypothesis which is quite general and is supported by other experiments which have nothing to do with noise. That is that a response to an unchanging situation cannot be maintained. In other words, attention cannot be constantly held on a display which is either stationary or changing only in a predictable way. More colloquially still, attention wanders when the display has lost its interest.

It is found, however, that the wandering of attention need only be very brief, even momentary, and that with a good state of motivation the subject can bring his attention back again to the monotonous task in something like 1½–2 sec. This shifting away and shifting back of attention Broadbent has called a mental blink, and this is a good expression because the analogy with eye blinks is quite close.

CONCLUSION

To summarize, let us see how these academic results might be applied to actual industrial situations. First, noise can produce physical damage to hearing. That we know about and it has been dealt with today. Second, noise is an annoyance and annoyance can certainly interfere with work, but the manner in which it does so is not yet the sphere of the experimental psychologist.

Third, we know that noise can directly interfere with some kinds of work. The intensity which has been shown to interfere is 100 dB, with a flat spectrum, and nowadays noise of this intensity will be frowned upon in any case. (That point is well to the fore with these experiments at present, but they do not last very long and we are told that the important thing is the integration of intensity with time, so these subjects only have a maximum test of 10 hr at 100 dB. They have an audiogram taken before and after.) It is likely that the effect which we can measure at 100 dB will still be present at lower intensities, but to what extent we cannot yet say.

Lastly, this interference will not affect the great majority of jobs. It will only be present when the job is such that continuous and rather monotonous attention is necessary. There are two types of industrial situation which are probably parallel to the two types of task in these experiments. First, there are watch-keeping jobs in which a human being forms the last link or safeguard in an otherwise automatic process. All the operator has to do is to sit and watch a number of indicators to see that all is well. In cases like this where, perhaps, a wandering of the attention may

result in an expensive mishap there is a very strong case for excluding loud noise.

Second, there are inspection tasks where a steady stream of objects is examined for some quality or property, and accepted or rejected accordingly. In such cases loud noises would be expected to lead to an increase in the small proportion of objects which are wrongly accepted.

Writing in 1934, Professor BARTLETT said: "Let us prepare for stories of broken nerves, of shattering headaches and irritable tempers. And should some psychologists, emulating, maybe, the methods of more remote sciences, try a few experiments and attempt to tell us that some of these heart-rending stories have less foundation than is imagined, let us not take too much notice of them. For surely we should not enjoy our civilization half as much as we do unless we could be frequently pointing out how thoroughly bad it is."

Since then a few psychologists have done a few experiments and, indeed, have shown that noise has effects which Professor BARTLETT did not then know about, but it is nice to know that these effects are in support of his point of view and not against it.

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DISCUSSION

Mr. I. K. MASON (U.K.A.E.A.) said that his Authority was carrying out a process which was at about 93 dB in the 2000–4000 c/s frequency and in the summer the conditions of temperature became very high. Actually something was being done about both those conditions, but they were continually getting comments from the workpeople that the effect of the noise would be all right if it were not so hot or that the heat would be all right if there was not so much noise. Could the author comment on the cumulative effect of noise and other things?

Dr. CARPENTER replied that the effect was likely to be considerable, although he did not know of any experiments in which a direct comparison had been made of the effects of noise and heat. It had been found that noise interacted with fatigue, and noise appeared to increase the effect of fatigue so that it was likely that there would be an interaction between noise and heat.

Surgeon Rear-Admiral S. G. RAINSFORD (Ministry of Labour), referring to the question of annoyance, asked whether any work had been done by means of a biochemical examination of people. If a person was annoyed he produced certain things such as adrenalin. Surely something could be done on those lines to find out the relation between the two.

Dr. CARPENTER replied that measuring the circulating adrenalin would be a very long way round. The blood pressure could be measured and, indeed, that had been done and it was known that there was a reaction to loud noise. When a person heard a tremendous bang his blood pressure went up, but it was a very short effect. No doubt there were longer-lasting things. The suprarenal gland was in the news at the moment. There might be a greater amount of hormone circulating but he had no special knowledge of that.

Dr. PETERS said that she remembered a doctor telling her that while a patient was having

a barium meal someone had dropped a pile of books on the floor and the patient's stomach had come up and gone down again. That had a rather interesting bearing upon noise.

Dr. CARPENTER said that the effect of a startling stimulus on the tone of the alimentary tract was well known, and that this was a nice illustration of it.

Mr. M. FLINN (Institute of Laryngology and Otology) asked whether, when a task was concerned directly with a loud noise such as conducting an orchestra, the loudness of the noise had the effect of impairing efficiency.

Dr. CARPENTER said that he did not know and had often wondered. He had studied an amateur choir of 400 people and the noise which they made was very considerable. He had estimated it at 100 dB, but yet people seemed to like it. It might be analogous with the shooting exercise which Mr. CAWTHORNE had spoken about.

Mr. K. MCLAY (Institute of Laryngology and Otology) asked whether any experiments had been done in silent conditions—conditions of extreme silence.

Dr. CARPENTER replied that he knew of none except that he did know of an experiment carried out involving a vigilance task. That had involved looking for nothing in particular to happen in a soundproof room. Sometimes when nothing seemed to be coming from the subject the experimenter had looked in and found him asleep, which was hardly surprising. Probably silence played some small part in that.

Mr. A. D. MULHOLLAND said that most of the tasks described by the author were repetitive to a high degree. He had also said that people of some academic standing were better able to concentrate. That would appear to lead to the conclusion that noise would not interfere with people doing design work.

Dr. CARPENTER said that that was not quite correct because it had been found that with people doing highly repetitive work, noise had no effect on their work. The reason for those particular tasks was that they were the kind of job which could be handled conveniently in an experiment. He had been asked questions by proof readers in the University Press about whether it was necessary to remove interfering noise. They claimed that they did not like it, but so far as he could tell from experiments made the effect of such noise could only be classed under the general heading of an annoyance. So far his Unit had not been able to handle that kind of thing.

Mr. G. G. PARFITT (Physics Department, Imperial College) said that, in view of what the author had said about the relatively small effects of noise on overall output, would he say from the factory manager's point of view that it was a fair inference that the reasons for trying to reduce noise were more cogent in the case of ear damage than in the case of psychological effects?

Dr. CARPENTER replied that it was difficult to make a comparison. The matter of damage to hearing was fairly well understood and was widely appreciated. It was also known that that was important where the noise level was high. But still there were people who found that noise of a lower level constituted an annoyance and interfered with their work. As to which was more important, it was difficult to say. The measurement of the noise in a factory would indicate into which category it fell. If it was 90 dB something should be done about it, but if it was less then the question arose as to whether it was worth while reducing the noise still further.

Dr. ROGAN said that as he understood it each of the experiments described by the author had lasted for 1½ hr. He could see no reason why a laboratory should not undertake experiments lasting for a full working shift of 4 hr with a break and then another 4 hr. The results obtained after 1½ hr might be entirely different from those obtained over a full working shift. He realized, of course, that there were limitations, but he thought that that could be done.

Apparently, young Servicemen had been used in one of the experiments. Surely it would not have been difficult to select subjects at random as to age and sex from the ordinary population? That again might have given entirely different results.

Dr. CARPENTER replied that both those points were mainly, although not entirely, a matter of practicability. With regard to the first question, they had not aimed particularly at 1½ hr.

The aim was to carry out the experiment for a sufficient time to show some effect. He had already pointed out that very brief tests had been the order of the day and they had shown no results. The 1½ hr was one step up. It was reasonable to suggest, however, that if the experiments had been longer lasting the effects would have been of the same type but more pronounced.

As to the second question, there was no reason to suppose that there would be any difference between the sexes. They were well aware of the difference between different kinds of people, and it was quite likely that if undergraduates had been used they would not have found so large an effect.

Dr. ROGAN said that he was still not convinced. Although it might be more in the realm of the social psychologist, it was thought that there were differences between the sexes. Ordinary experience in industry where there was a mixed population indicated that when carrying out exactly the same task the response between the sexes was quite different. He imagined that it would be difficult to carry out such an experiment in the laboratory, but when the author said that he would not expect to find differences he thought that he would in fact find differences.

Dr. CARPENTER said that there had been some interesting letters written about women's supposed sensitivity to high-pitched screaming noises which men did not suffer from, but there was as yet no evidence about it.

Dr. PETERS said that she would advise the last speaker to go into a certain café in Merthyr Tydfil in the middle of the morning and hear the noise there!

They had been told that noise above the normal speaking level might do harm. Looking at the different values of different noises in ordinary life, it seemed to her that to say to industry that noise at that level was harmful was tantamount to saying that all the noises which they took in their stride might be harmful. That would have a very fundamental psychological effect and that was one of the great difficulties. It was difficult in industry to convince people that what they had been accustomed to for years could cause damage. Unless that could be got across somehow, not very much would be done.

Dr. CARPENTER said that he agreed, and added that many people cheerfully accepted noise. They had already had the example of people who went to orchestral concerts. In their recreational pursuits people accepted noise levels which were probably quite dangerous. Another example was the noise level at suburban cinemas.

Dr. F. V. TIDESWELL said that the author had spoken mainly of manual tasks. Had he appreciated the extreme difficulty of carrying out an auditory task against a background of noise? Listening to a signal, for instance, against a background of noise was very difficult.

Dr. CARPENTER said that he did not deny that. The effect of noise on auditory tasks was an entirely different field, and a lot of work had been done in relation to the Forces regarding the intelligibility of speech against various background noises. So far as nuisance was concerned, they still did not really know how to handle that.

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"HAS YOUR WORKER A NOISE PROBLEM?"

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INTRODUCTION

IN the sphere of noise hazards, the question which frequently confronts managerial staff, occupational hygienists and industrial medical officers is: "Has a particular employee, or group of employees, a noise problem?"

The answer to the question must be based on a consideration of the various deleterious effects of noise in the industrial intensity range, i.e. overall levels up to 120 dB S.P.L. These deleterious effects can be arbitrarily classified as follows:

1. Interference with communications
2. Undue loudness
3. Annoyance
4. Influence on behaviour
5. Impairment of hearing
6. Physiological effects
7. Increase of accident rate

Individual consideration of whether any of these factors is creating a problem will decide whether there is a noise problem in general.

I shall attempt to emphasize aspects not stressed by the speakers at the Conference, but, in an effort to maintain coherence and obtain an integrated paper, some overlap is inevitable.

1. INTERFERENCE WITH COMMUNICATIONS

The disruption or "masking" of speech communication by noise may occur at relatively low levels of sound intensity and is, as DAVIS (1951) remarks, probably the most deleterious effect which it has on man's behaviour. Work output is probably most sensitive to noise when it depends on speech communication.

As TONNDORF (1951) says, amongst the factors which are of importance in working towards a solution of this problem is a thorough understanding of both the capabilities and limitations of the human ear in differentiating sound signals from noise backgrounds. It is not merely a question of the signal-to-noise ratio. The basic process involved in the problem is masking, i.e. the phenomenon of the threshold for one signal being raised by the simultaneous presence of a second signal.

The masking of pure tones by other pure tones was first investigated systematically by WEGEL and LANE (1924), whilst the masking effect of white noise on pure tone and speech perception has been studied by FLETCHER and MUNSON (1937), FRENCH and STEINBERG (1947) and HAWKINS and STEVENS (1950). The main features of auditory masking are well summarized by HIRSH (1952), who points out that the unifying concept in these matters is provided by FLETCHER's (1940) critical band. The critical band is derived from two assumptions: first, the only

important frequencies for masking in a given noise are those frequencies which are within a small band centring around the frequency of the pure tone being masked; second, when a tone is just audible in a given noise, the total energy in this critical band of frequencies is equal to the energy of the tone. The width of the critical band is not the same at all frequencies.

Speech, like many other complex sounds, has a particular frequency-intensity pattern. Moreover, experiments at the Bell Telephone Laboratories have shown that within the speech frequency range, different frequencies vary in their relative importance for speech intelligibility (FRENCH and STEINBERG, 1947).

It is possible, by means of a so-called articulation index which is based on the sound spectrum as well as the overall intensity of a noise, for acoustics engineers to calculate in advance the effect which a particular noise will have on the ability to communicate speech. However, as HIRSH *et al.* (1954) point out, the intelligibility of words is a function not only of their physical characteristics but also of such factors as word probability in the language and similar contextual clues. Thus FRENCH and STEINBERG's (1947) articulation index, which is calculated from physical characteristics alone, will predict best the intelligibility of items which depend exclusively on physical characteristics, e.g. nonsense syllables.

Word probability, or rather the probability that a certain information unit will be conveyed, is implicit in the second premise of the Wiener–Shannon theory of communication (WIENER, 1948; SHANNON, 1948; and FANO, 1950), but even the consideration of the complicated quantistic and statistical concepts of information theory as well as the physical parameters of noise and speech would not give an absolutely satisfactory prediction of the masking effect of noise on speech communication. SALTZMAN (1949) was impressed with the variability of this masking effect between individuals. This inter-individual variation he attributes to that dimension of sensation concerned with the ability to concentrate and termed by TITCHENER (1924) "attensity".

Another factor, which is operative in general conversation, or in person-to-person conversation in reverberant rooms, is the masking of consonants by vowels. Vowel frequencies centre around 500 c/s whilst consonant frequencies centre on 3000–4000 c/s. There is thus the possibility of vowels masking consonants when the speech intensity is high enough to produce harmonics. This would occur in factories where the overall S.P.L. is about 90 dB, when the workers must shout as loud as possible to be heard. The combined masking of consonants owing to ambient noise, together with the masking by the vowels, will markedly reduce the intelligibility of speech (TUMARKIN, 1954).

The differential effect of noise, and of various types of noise, on the ability to hear the various vowels and consonants has been investigated by MILLER and NICELY (1955), who have worked out confusion trees.

An attempt to furnish data for evaluating wide-band noise fields in respect of their interference with speech is provided by the so-called Speech Communication Criteria (BERANEK, 1950; PETERSON, 1951; PARRACK, 1951). Four speech communication criteria are given. They are labelled S.I.L. – 75, 65, 55 and 45. S.I.L. comprises the initial letters of "speech interference level" and the number in the code is the average S.P.L. for the three octave bands, 600–1200 c/s, 1200–2400 c/s and 2400–4800 c/s.

In noises whose spectra conformed to the S.I.L. −75 contour, personnel would have to speak in a very loud voice and use a selected and possibly prearranged vocabulary to be adequately understood over a distance of about 1 ft. The maximum overall S.P.L. of noises meeting this requirement would be of the order 110 dB. Just reliable communication by raising the voice over a 2 ft distance or shouting over a distance of 8 ft should be possible in noises whose spectra conformed to the S.I.L. −65 contour. In noise fields of the S.I.L. −55 contour type, communication should be effective with a normal voice at a distance of 3 ft, or with a very loud voice from a distance of 12 ft, whilst normal conversation should be possible over 12 ft when the noise conforms to the S.I.L. −45 contour (PARRACK, 1952).

An alternative to Beranek's octave-band method for assessing the intelligibility of person-to-person speech under noisy conditions is the method of PICKETT and KRYTER (1955). In this method, the S.P.L. for each of the octave bands 300–600 c/s, 600–1200 c/s, 1200–2400 c/s, 2400–4800 c/s and 4800 c/s up is multiplied by a factor 1, 1, 2, 2 and 1 respectively. The total of these weighted measures is then averaged by dividing by 7. Table 1 shows the maximum permissible weighted average noise for 80 per cent word intelligibility at two distances and for three conditions of vocal effort.

TABLE 1. MAXIMUM PERMISSIBLE WEIGHTED AVERAGE NOISE FOR 80 PER CENT WORD INTELLIGIBILITY

Vocal effort / Distance talker–listener	Normal (Long R.M.S. S.P.L. 1 m from lips = 65 dB)	Loud (Long R.M.S. S.P.L. 1 m from lips = 71 dB)	Very loud (Long R.M.S. S.P.L. 1 m from lips = 77 dB)
At ear (1 in.)	86	92	96
4 ft	52	58	62

We can therefore summarize the interference-with-communication effect of noise by saying that, far from being due merely to the signal-to-noise ratio, it is dependent on a complex of factors ranging from precise physical ones to less tangible psychological phenomena. For person-to-person speech in noise, however, good predictions of the intelligibility can be obtained from the results of octave band analyses. The methods of BERANEK (1950) or of PICKETT and KRYTER (1955) may be used.

2. UNDUE LOUDNESS

Loudness may be a factor in the "annoyance value" of a noise, but it is here given special consideration because it is one of the chief psychological dimensions of what we hear. Thanks to the work of STEVENS (1936, 1955, 1956 and 1957) and his collaborators, we can now measure loudness and calculate the loudness of continuous spectra. Loudness is the subjective strength of a sound as heard by the typical (=median) listener, and, as STEVENS and TULVING (1957) remark, its estimation can be performed by untrained observers in a relatively diffuse sound

field in lieu of earphones. The unit of loudness is the sone, which was originally defined as the loudness of a 1 kc/s tone 40 dB above threshold (STEVENS, 1936). It is now defined as the loudness of a 1 kc/s tone at 40 dB S.P.L.

The relationships of sones to phons is given by the equation:

$$\log S = 0{\cdot}03\,P - 1{\cdot}2$$

where S = loudness in sones

and P = loudness level in phons

STEVENS (1957) gives a chart from which it is possible to calculate the loudness of a complex noise from an octave band analysis. Unfortunately, although the method is satisfactory for approximately steady noises, it does not predict very well the loudness of sharply intermittent noises or those having line spectra.

To obtain an idea of the dimensions of the sone scale, the loudness of some typical noisy industrial conditions is shown in Table 2.

TABLE 2

Condition	Overall noise level (dB S.P.L.)	Loudness (sones)
1. Automatic lathe 3 ft away ..	95	72
2. Annealing furnace 4 ft away	101	98
3. Pneumatic hammer 3 ft away	102	280
4. Nail machine 4 ft away ..	110	250

It should be noted that two noises of similar overall sound pressure level may differ in loudness by a factor of nearly three. Moreover, a noise which has a higher overall level than another noise may be quieter. This is because two noises of a similar overall level, e.g. that of the annealing furnace and that of the pneumatic hammer, may have widely different spectra. The furnace noise consists of a preponderance of low-frequency energy, whilst the hammer noise consists predominantly of higher-frequency energy. As REESE and KRYTER (1944) showed, the loudness of bands of noise of a given sound pressure level increases when the constituent frequencies in the noise band are increased.

As a rough measure, an increase in the overall level of a given noise by 10 dB produces a doubling of the loudness. Conversely, a fall in the overall level by 10 dB results in halving of the loudness.

3. ANNOYANCE

The "annoyance value" of a noise is governed by the following factors:

(1) *Frequency composition*

This is as important as the intensity of the noise. Just as "equal loudness" contours were worked out for pure tones by FLETCHER and MUNSON (1933), and for bands of noise by REESE and KRYTER (1944), so have "equal annoyance contours" been determined by LAIRD and COYE (1929) for pure tones, and by REESE and KRYTER (1944) for bands of noise. The function relating "annoyance value" to frequency is not entirely due to the variation of loudness with frequency, since,

above about 2 kc/s, Reese and Kryter's equal-annoyance curves fell below the equal-loudness curves at the rate of about 4·5 dB/octave.

(2) *Intensity*

Sound levels as low as 90 dB S.P.L. may produce feelings of unpleasantness on the part of some subjects (Finkle and Poppen, 1948), although Davis (1941) reports that most persons exposed to levels as high as 120 dB S.P.L. as a matter of course in their work apparently become indifferent to it. Recently, Spieth (1956) has obtained annoyance threshold judgments for noise. Individuals were asked to adjust the intensity of a noise to a level which, if any louder, would annoy them if it were present most of the time where they were working. For individuals who were working, or had once worked, in high noise levels, the median annoyance threshold for random noise was 88 dB S.P.L.

(3) *Modulation* (Miller, 1947)

Loudness and pitch modulation is a factor in annoyance since subjects prefer to listen to continuous, unchanging sounds. This is probably the underlying phenomenon in Cassel and Dallenbach's (1918) demonstration of the inability of subjects to adapt as easily to intermittent noise as to continuous sounds.

(4) *Reverberation*

"Spreading" or lack of localization of noise contributes to its annoyance value (Sabine and Wilson, 1943).

(5) *Susceptibility of the listener*

After a searching investigation, Miller (1947) concluded that the annoyance of a noise depends primarily upon the particular listener and the particular situation in which he finds himself. Thus it may be relatively easy to annoy a sensitive subject engaged in difficult mental work.

(6) *Inappropriateness* (Kryter, 1950)

(7) *Duration of the sound* (Dickson, 1953)

(8) *Content and degree of steep-fronted waves* (Littler, 1954)

(9) *Unexpectedness*

This is not a function of sound alone but is merely a special application of the startle reaction which can be achieved by other stimuli.

The essentially psychological nature of this effect of noise is reflected in the remarks of Rosenblith *et al.* (1953): "People will continue to investigate the problem of annoyance by noise. It is to be hoped that they will be able to find at least a partial answer to the problem by adopting a reasonably operational definition of the annoyance concept in their experiment or opinion poll."

4. INFLUENCE ON BEHAVIOUR

From the productivity angle, data on the effects of noise on output and efficiency are clearly of prime importance. The classical field study was that of Weston and Adams (1932 and 1935), who investigated the performance of weavers by reducing (by wearing ear plugs) the sound to which they were exposed. These results, however, and their interpretation, have been subject to severe criticism by both Berrien (1946) and Kryter (1950).

DAVIS (1951) stated that steady or expected noises do not adversely affect psychomotor activity to any significant extent and, in fact, noise may actually "insulate" a person from environmental distractions. However, recent studies at the Medical Research Council Applied Psychology Research Unit have shown conclusively that, under certain conditions, intense noise may decrease efficiency.

Noise levels of 100 dB S.P.L. impair general efficiency in some vigilance tasks (BROADBENT, 1952). In a very continuous task allowing no breaks for rest, momentary errors and aberrations will occur in noise although work in between these errors will be quite unaffected (BROADBENT, 1957a). Overall noise levels of more than 90 dB S.P.L. are required to produce these effects, and high-frequency noises are more effective than low-frequency ones (BROADBENT, 1957b). FRISBY (1954) remarks that a steady level of noise, even if considerable, has less effect than a lower level but intermittent or varying noise.

A "distraction" view of noise is favoured by BROADBENT (1953), and JERISON (1957) suggests that shifting attention is disturbed more by noise than is sustained attention. CARPENTER (1958) contends that meaningless noise can be considered to be a non-specific form of mental stress comparable to high atmospheric temperature.

To summarize the effects of noise on behaviour we can say that, under appropriate conditions, noise with overall level not less than 90 dB S.P.L. may have a detrimental influence on certain aspects of work output and efficiency.

5. IMPAIRMENT OF HEARING

This effect has been discussed by both Dr. LITTLER and Mr. CAWTHORNE, who have pointed out that intense noise may produce irreversible cochlear damage which shows as a progressive high-tone perceptive-type hearing loss, the so-called occupational deafness.

The factors which determine whether permanent cochlear damage due to noise will be produced and the degree to which it will occur have been mentioned by BØRGE LARSEN (1952) and by DICKSON (1953). The factors can be listed as follows:

(1) Sound intensity
(2) Total time of exposure to noise
(3) Length of exposure per period
(4) Frequency composition of the noise
(5) Character of the sound, i.e. continuous or discontinuous
(6) Environment
(7) Noise sensitivity of individual
(8) Condition of ear(s), i.e. initial threshold of hearing; presence or absence of aural pathology.
(9) Age of individual
(10) Protection afforded to the individual.

As Dr. LITTLER remarked, these factors can be largely integrated in a single expression to define whether a given noise is, or is not, dangerous to hearing. The Damage Risk Criterion (=D.R.C.) specified the maximum S.P.L. of noise as a function of frequency to which people should be exposed if the risk of hearing loss is to be avoided. The levels are considered safe in terms of exposure during working days for durations up to a lifetime and apply to noise which has a reasonably continuous time character with no substantial sharp energy peaks. Various

D.R.C.s have been put forward, but that calculated by BURNS and LITTLER (1956) from data given in the American Z.24-X.2 report is probably near the truth (LITTLER, 1958). This D.R.C. agrees fairly well with one deduced experimentally from auditory fatigue data (HINCHCLIFFE, 1957).

As with noises in general, the spectra of industrial noises show diverse forms and no one industrial noise has a spectrum conforming to BURNS and LITTLER's D.R.C. Consequently it is impossible to lay down a single overall sound pressure level which must not be exceeded if the noise is to remain innocuous. However, bearing in mind that the D.R.C. is only a statistical concept, and having consideration for the spectra of industrial noise in general, one can say that a noise of overall level of 90 dB S.P.L. indicates the borderline between innocuous and injurious levels. This limiting condition is for daily exposure times of less than 8 hr working sessions. For shorter daily exposure times, higher intensities may be permitted. ELDRED *et al*. (1955) point out that, assuming the risk of cochlear damage is dependent on the total acoustic energy delivered to the ear in a given exposure session, the allowable noise levels can be increased by 3 dB for each halving of the exposure time. Thus, for short-term exposure to the spectrum of typical jet-exhaust noise, a maximum permissible overall level of 100 db S.P.L. for 8 hr may be equated with 10 sec exposure to an overall noise of 135 dB S.P.L., the maximum intensity permissible for unprotected ears for any duration. This energy-duration concept has now been incorporated in U.S. Air Force Regulation No. 160-3.

Unfortunately, the D.R.C. specifies limiting acoustical environmental conditions for groups of people only. The criterion leaves out the question of noise hazard for the individual worker, for whom it cannot make a forecast. This is because of the factor of individual susceptibility. Contrary to a recent assertion (BROADBENT, 1957a), investigations into individual susceptibility to acoustic trauma are not new. In 1929, TEMKIN had the idea that a personal prophylaxis for potential workers in noisy industries should be based on an auditory fatigue test. In 1940, PEYSER introduced such a test. This test was modified by WILSON (1943 and 1944), by KIML (1947), by PEYSER himself (1947) and finally by THEILGAARD (1949). More recent tests, using noise in lieu of pure tones as the stimulus, have been proposed by WHEELER (1949), by GREISEN (1951) and by GALLAGHER and GOODWIN (1952). The test proposed by the last-named workers seems the most promising. Recently, JERGER and CARHART (1956) have made a contribution to this field of study, whilst LAWRENCE and BLANCHARD (1954) determine the threshold of distortion as an index of noise susceptibility.

Predictive tests employing temporary threshold shifts are already in use in two countries. A test using a 105 dB S.P.L. noise stimulus is given in Denmark as part of a pre-employment physical examination (CHRISTIANSEN, 1956), whilst a test using a pure tone stimulus is employed for personnel selection by the Czechoslovakian Air Force (KIML, 1947). However, despite these practical applications and a partial validation by JERGER and CARHART (1956), a proven, acceptable predictive test for noise susceptibility is not yet available.

Consequently, it devolves upon audiometry to indicate which particular workers are suffering, or have suffered, from noise-induced hearing defect.

The methodology of industrial hearing tests using classical clinical pure-tone audiometry has now reached an established form (HINCHCLIFFE and LITTLER, 1958).

A single audiogram, it should be noted, is practically useless. Until recently, a high-tone notch on the threshold audiogram, with a peak loss about 4 kc/s, was considered pathognomonic of acoustic trauma. However, such notches may be congenital; they may also be due to head injuries (SCHUKNECHT, 1950), and SØHOEL's (1957) work indicates that they may be a *sequela* of otitis media. Other causes are also likely. Consequently, even when the high-tone notch shows a positive recruitment phenomenon and diplacusis is present, we can say no more than that there is cochlear damage. The single threshold audiogram gives no clue to the ætiology. Therefore, as Dr. LITTLER mentioned in his paper, serial audiograms are required.

A gradual deterioration over the years in the auditory threshold of a worker in a noisy industry is, again, not pathognomonic of a noise-induced hearing loss. A progressive conductive deafness, for example otosclerosis, must be excluded, whilst a general medical and a specific audiological examination will search for causative factors of a progressive perceptive deafness. Too much reliance cannot be put on the form of the audiogram in noise-induced hearing losses, as in audiologic diagnosis in general. Individuals vary. Apart from variations in the peak frequency of the classical high-tone notch between 3 kc/s and 6 kc/s, shallow troughs peaked at 2 kc/s may occur or, more frequently, the audiogram shows a fall-off, usually sharp, from a frequency of 2 kc/s or more.

When other possible factors have been excluded from the ætiology of a progressive high-tone loss, the ageing process must be considered. Various trend, or presbycusis, curves have been reported. These curves show the elevation of the threshold of hearing which occurs with increase in age. The differences between the results given in various papers are most probably due to sampling error. Although none are unequivocally acceptable, the presbycusis curves of HINCHCLIFFE and LITTLER (1957) (see Fig. 1) are probably near the truth.

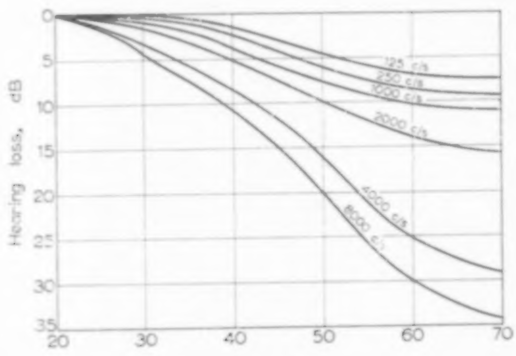

FIG. 1. Tentative presbycusis curves. Threshold of hearing as a function of age. Reference zero is threshold at age 20 years. After HINCHCLIFFE and LITTLER (1957).

A limited differentiation of noise-induced hearing loss from presbycusis is possible in that the hearing defects due to the latter condition never show a "notched" threshold audiogram and the majority of cases do not show, or incompletely show, loudness recruitment (PESTALOZZA and SHORE, 1955). Moreover, the discrimination

loss for speech in presbycusis is, in general, more marked than one might expect from a consideration of the pure-tone audiogram (GAETH, 1948).

After correcting the serial audiograms of a worker in noise for the ageing effect, there may still be an appreciable progressive perceptive hearing loss, involving the higher frequencies. Before concluding, in the absence of evidence of other ætiologic factors, that the case is one of noise-induced hearing loss, an abiotrophy must be excluded. The abiotrophies, or heredo-degenerative perceptive deafnesses, have more recently been delineated (CAWTHORNE and HINCHCLIFFE, 1957) and will be indicated by a history of familial deafness. Of course, one must ensure that familial incidence of deafness is not merely due to the family following the same noisy occupation. It must be cautioned, too, that the absence of a family history may merely indicate a sporadic abiotrophy. Such a case would be indicated by a worker presenting a progressive elevation of the threshold of hearing out of all proportion to similarly-exposed individuals, and out of all proportion to that expected from measurements of his acoustic environment.

As has been stressed previously, noise-induced hearing loss may be temporary or permanent. The remarks in this section have referred to permanent noise-induced hearing loss. Consequently, when audiometry is undertaken in industry, precautions must be observed to exclude reversible, i.e. temporary, changes. The Guide for Conservation of Hearing in Noise published by the American Academy of Ophthalmology and Otolaryngology recommends that at least 16 hr should have elapsed since any previous noise exposure.

From the foregoing it is clear that measurement of workers' hearing must be made whenever the spectrum of the environmental noise approaches, or passes, the Damage Risk Criterion. In the event of octave band analyses of the noise not being available, we would say that the audiometry is indicated if the overall level is greater than 90 dB S.P.L. Often, even one overall noise level measurement is not available. In such cases, the criterion of a hearing conservation programme should be based on clinical considerations. As the *Guide for Conservation of Hearing in Noise* mentions, these indications are:

(1) Difficulty in communicating by speech by workers while they are in noise;

(2) Head noises or ringing in the ears after working in the noise for several hours; and

(3) A loss of hearing that has the effect of muffling speech and certain other sounds after several hours' exposure to the noise.

6. PHYSIOLOGICAL EFFECTS

Although MORGAN (1917), SMITH and LAIRD (1930) and KENNEDY (1936) have reported physiological reactions to noise, most of these could be considered to be more in the nature of startle responses, whilst the experiments themselves were open to criticism. More recently, the whole question of physiological responses to noise was comprehensively investigated by FINKLE and POPPEN (1948). They exposed men to turbo-jet engine noise of 120 dB S.P.L. and the subjects were investigated with respect to pulse rate, respiratory rate, blood pressure, basal metabolism, visual acuity, bleeding and clotting time, blood sedimentation rate, and icteric index, whilst electrocardiographic, electroencephalographic, thoracic

and abdominal radiographic and renal function tests were also undertaken. The results indicated complete adaptation to the noise. However, recently DAVIS *et al.* (1955)* contended that electrodermal responses, muscle-action potentials, respiration and pulse-rate increase with increase in intensity of a sound stimulus, especially when the latter exceeds 90 dB S.P.L. It seems possible, therefore, that there may be some physiological changes in individuals working in noise levels greater than 90 dB O.A.L.

7. INCREASE OF ACCIDENT RATE

Industrial deafness consequent on subjection to noise is said to be associated with a high accident rate (SALMONT, 1938).

ASSESSMENT

We have already seen that the *potential* noise hazard (or acoustic stress) is indicated by an analysis of the noise, but the actual noise hazard (or acoustic strain) can be determined only by measurement of the phenomena that are impaired.

As FLEMING (1958) remarked, no single feature can characterize a noise completely. An octave-band analysis of the noise is required to determine how loud the noise is, to assess to what extent it will interfere with speech communication and whether impairment of hearing might ensue. This analysis will also give us an idea of how annoying the noise might be and whether it might influence work output and efficiency.

If facilities are not available to determine the noise spectrum, an overall noise-level reading is useful in assessing the potential hazardousness of the noise. For this purpose, the Dawe Sound Level Indicator Type 1408B can be used. An overall sound level less than 85 dB S.P.L. indicates an almost certainly "safe" acoustic environment, whilst overall levels of 85 to 95 dB S.P.L. indicate possibly hazardous or undesirable conditions. Overall levels in excess of 95 dB S.P.L. merit a noise control programme.

If even an overall sound-level meter is not available, then the potentially hazardous noisy environment must be determined by clinical considerations. PARRACK and ELDREDGE (1951) consider that the highest S.P.L. that will allow direct speech communication with a loud voice between persons separated by a distance of 6 ft is the maximum for safety both for the ear and for the prevention of accidents. Under these circumstances, S.P.L.s as high as 95 or 100 dB would be allowed for octave bands below 150 c/s, but S.P.L.s for all other octave bands up to 10 kc/s must not be greater than 85 dB. SATALOFF (1957) frames his criterion for a potentially hazardous noisy environment in the question: "Is it so noisy that you have to raise your voice to be heard?"

The measurement of the *actual* noise hazard in respect of behaviour is not practicable under industrial conditions, whilst complicated articulation test procedures are required for measuring communications interference. Fortunately, the only permanent effect that noise can have on individuals can be directly measured, and easily so. This is the determination of the degree of impairment of hearing. If noise-induced hearing losses are only suspected in a particular group of workers,

* Since these workers used an intermittent 1 kc/s stimulus for 2 sec each minute, it may be arguable that this is more akin to a startle reaction.

full frequency scale threshold of hearing determinations need not be made. Single frequency screening audiometry may be employed, since more than 99 per cent of industrial workers will show no greater hearing loss at 4 kc/s than at a lower frequency (HOUSE, 1957). A suitable available instrument is the battery-powered, transistorized Ambco Model 800 "Oto-Chek", which provides a 4 kc/s test tone at screening levels equivalent to 20, 35 and 50 dB hearing loss. As HOUSE (1957) remarks, sound-treated test rooms for these instruments are unnecessary, since the ambient noise in most offices has a negligible masking effect at 4 kc/s. Moreover, the simplicity of such instruments dispenses with highly-trained operating personnel.

Should screening audiometry indicate a significantly high incidence of hearing defects in a group of workers in a noisy location, then standard clinical threshold audiometry must be employed. Pre-employment audiometry must also be arranged for further entrants into that industry. Furthermore, all individuals with significant hearing defects should have an audiologic assessment with full diagnostic audiometry.

SUMMARY

The answer to the question "Has your worker a noise problem?" depends on an appraisal of the nature of the acoustic environment. A noise analysis alone will only indicate the *potential* hazard. The *actual* hazard must be directly measured. Permanent noise-induced hearing losses may be discovered by single-frequency screening audiometry, but the degree and course of these defects can only be determined by serial full-frequency threshold determinations.

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THE ANALYSIS AND CONTROL OF VIBRATION

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INTRODUCTION

ALMOST all the mechanical processes of industrial production necessarily give rise to a greater or lesser degree not only of noise but of mechanical vibration. Machinery is essentially rotary, reciprocating or impulsive, or some combination of these, and all but a perfectly-balanced, uniformly-loaded rotating machine must cause some vibration in itself and its surroundings. Increased mechanization and increased speeds of production are tending to heighten the problems associated with vibration in industry.

The adverse effects of vibration are various: enhanced wear and uneven running of machinery, fatigue and breakage of structural and running members, cracking of masonry, discomfort, annoyance and possibly injury to human beings are examples. This brief survey will be primarily concerned with the human aspects of the problem.

The handling of a vibration problem explicitly or implicitly involves three steps:

(1) Measurement of prediction of the levels of vibration produced by a source at the various points of interest.

(2) Establishment of criteria for the acceptable levels at these points.

(3) Modification of the system to reduce the actual to the acceptable levels.

The following discussion of vibration problems can conveniently follow this same sequence.

1. MEASUREMENT OF VIBRATION

In general the wave forms of stress and of motion of a vibrating body are complex and are most readily regarded as resolved into their sinusoidal Fourier components (as discussed in Dr. LITTLER's paper, for example). Thus it will be for the most part convenient and sufficient to discuss the properties of sinusoidal vibrations. The usual frequency range of practical interest extends from a few cycles per second to several hundred cycles per second. Again, any point on a vibrating member has in general components of motion in each of the three co-ordinate directions, though often one of them predominates in magnitude or importance, for example the motion of a metal panel normal to its surface. Most vibration detectors respond primarily to motion in one specific direction and so with appropriate techniques can be used to measure the three components in turn where necessary.

Vibration measurement essentially involves the determination of some magnitude associated with the sinusoidal frequency components of the relative motion between the surface of the body concerned and a suitable reference body. Some form of sensing element is employed to detect and indicate the required magnitudes of this relative motion. It is convenient to distinguish three cases or categories in which the reference body is differently supported.

Category 1

The reference body is fixed to some stationary support (as indicated in Fig. 1 (i)). The relative displacement is then equal to the actual displacement of the vibrating body. This system is the fundamental one but is rather seldom used in the field

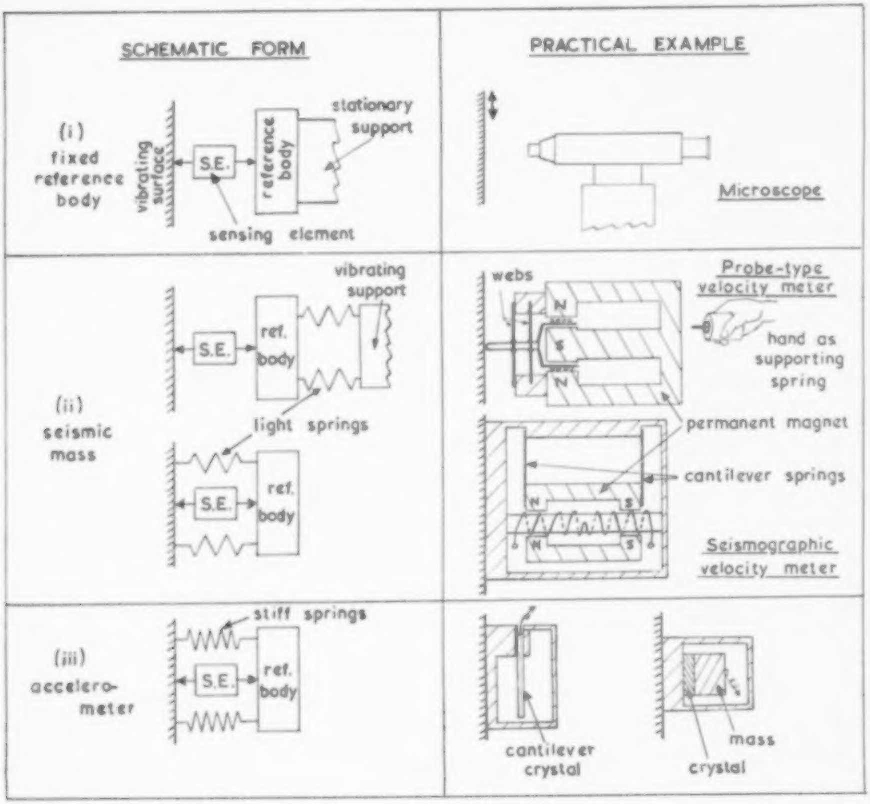

FIG. 1. The three basic categories of vibration detector, with some representative practical examples. (Schematic and not to scale.)

since a truly stationary support is often hard to find (e.g. near a powerful machine) and the usually rather critical positioning of the fixed support near the vibrating body is often tedious.

Category 2

The reference body is a relatively heavy mass mounted on light springs attached to any convenient support, not necessarily stationary (Fig. 1 (ii), first case), or to the vibrating body itself (Fig. 1 (ii), second case). In practice both forms of spring are usually present. If the natural frequency of free vibration of the reference body, here the so-called seismic mass, on the springs is well *below* the frequencies to be measured, the mass will remain sensibly stationary, and the system behaves as in Category 1 above. The previous requirement of a stationary support is now

removed, however, and the difficulties of positioning usually mitigated. For example, the light supporting springs of the first case of Fig. 1 (ii) may consist merely of the hand and arm of an operator, which are flexible enough for many purposes.

Category 3

The reference body is here conversely a light mass supported by stiff springs from the vibrating body (Fig. 1 (iii)). The reference body now virtually follows the vibrating one in its motion, and in particular they have essentially the same acceleration, a. The force F in the springs causing the movement of the reference body, of mass M, will be the product Ma. This force F produces a small extension $e = F/S$ in the springs of stiffness S, giving a small residual relative motion of the same amount between the two bodies. Thus

$$e = F/S = Ma/S \tag{1}$$

i.e. the relative displacement is proportional to the acceleration. If, as is common, the sensing element gives an output proportional to e, the system becomes an "accelerometer". It is a very simple device to use since it is essentially a small, light but robust object attached directly and solely to the vibrating body. Also, acceleration is in many cases the feature of a vibrating system which is of particular interest. Most commercial vibration pick-ups are of this type. With this system, as with all the others, it is important that the effective mass attached to the vibrating body should be sufficiently small not to influence its motion appreciably. (This may not be too easy to achieve on something like a thin metal panel.) It can be shown that, for equation (1) to hold, the natural frequency of the reference body on the springs should be *large* compared with the frequencies to be measured, the opposite requirement from that in Category 2. Since it can be shown that

$$f_0 = \frac{1}{2\pi}\left(\frac{S}{M}\right)^{\frac{1}{2}} \tag{2}$$

the requirement of stiff spring and small mass follows. A careful choice of the damping applied to the sprung mass permits the instrument to be used as close as possible to f_0.

The sensing element may take widely differing forms, but usually gives a useful output proportional either to the displacement of its "working terminals" relative to each other (e.g. direct visual devices such as the microscope, mechanical and optical levers, strain gauges, piezoelectric or electrostatic pick-ups, variable reluctance gauges) or to the rate of change of this displacement (electrodynamic pick-ups). An element of the first type used with systems of Category 1 or 2 above gives an instrument usually termed a "vibrometer" and indicating vibrational displacement, while if Category 3 is used an accelerometer results. The second type of sensing element with systems of Category 1 or 2 gives a "velocity meter".

If the vibration is sinusoidal the peak displacement (u), velocity (v) and acceleration (a) are immediately related, since

$$v = 2\pi f u \quad \text{and} \quad a = 2\pi f v = (2\pi f)^2 u \tag{3}$$

where f is the frequency. Where this is not the case, it is still possible to determine the three quantities from a single vibration pick-up by use of electrical integrating or differentiating circuits incorporated in the amplifier.

Probably the simplest type of vibrometer is that shown in Fig. 2 (a) and consists

of two oblique straight lines on a piece of paper gummed to the vibrating surface. If the latter undergoes fairly large continuous vibration parallel to itself at a frequency of some 15 c/s or above, images of the figure in its two extreme positions

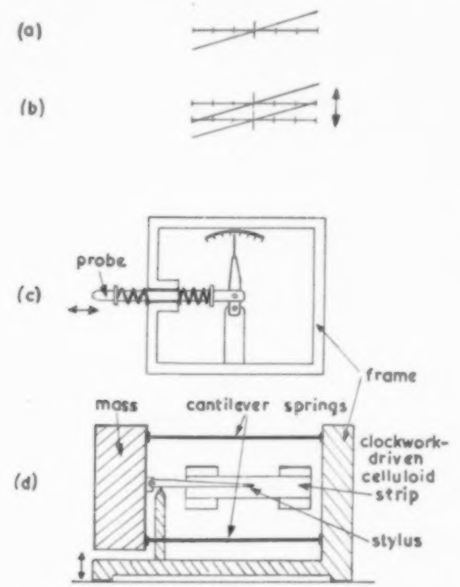

FIG. 2. Some simple types of vibration detector. (*a*) The straight-line figure; (*b*) the same viewed under vertical vibration; (*c*) the mechanical lever vibrometer; (*d*) the mechanical vibrograph.

are seen simultaneously, as in Fig. 2 (*b*), and the amplitude can be read off directly. This is an instrument of Category 1, since the eye is stationary, as also is the microscope on a rigid base, which can be used for smaller amplitudes, particularly in conjunction with stroboscopic illumination.

A somewhat more elaborate instrument is the mechanical vibrometer. Fig. 2 (*c*), where a probe lightly sprung within a hand-held casing is pressed against the test surface and causes a pointer to vibrate with magnified amplitude across a scale (Category 2). The same mechanism, usually in the seismograph form, is used in the vibrograph, where a vibrating stylus lever pivoted on a seismic mass makes a permanent wave form record on a moving celluloid strip (Fig. 2 *d*). Vibrographs of this kind may be usable down to frequencies of some 10 c/s and amplitudes of 0·0005 in.

An elementary mechanical form of frequency analyser consists of a thin metal reed of variable length (Fig. 3). The device is held against the vibrating object, and the length varied by means of a knurled traversing knob until the reed comes into visible oscillation due to resonance with some component in the vibration. The relevant frequency is then read off on the scale of reed lengths.

For detailed study of vibrations it is necessary, however, to use more sophisticated equipment in the form of an electrical vibration pick-up and amplifier, if necessary with appropriate display, recording and analysing gear.

Some representative electro-mechanical pick-ups are shown on the right of Fig. 1. The probe-type velocity meter resembles a moving-coil loudspeaker or microphone with the probe replacing the diaphragm. It is held by the hands, which form the

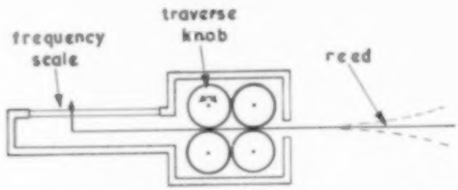

Fig. 3. The variable-length reed vibration analyser.

light supporting spring, with the probe lightly pressed against the vibrating surface. Motion of the coil through the radial magnetic field produces an e.m.f. in it. The second example shown is essentially a seismograph, the instrument being attached bodily to the vibrating surface, with light cantilever springs which support a permanent magnet and allow it to remain at rest within the casing. The useful e.m.f. induced in the coil is again proportional to the relative velocity between it and the magnet. With velocity pick-ups, velocities down to 0·001 in/sec may typically be measured with sensitivities of the order of 0·01–0·1 V per in/sec. The output is at low electrical impedance, permitting the use of long connecting cables to the amplifier.

An alternative type of instrument, indicating displacement, allows a small ferromagnetic body forming a part of the magnetic circuit of a solid-cored inductance to move relative to the rest. The motion varies the reluctance of the magnetic circuit and hence the electrical inductance of the coil, which may be connected in a high-frequency a.c. bridge circuit or as the frequency-determining element in an oscillator circuit. Appropriate electrical networks observe the variations of balance current or oscillator frequency respectively. These devices are usable down to zero frequency.

The accelerometers shown in Fig. 1 (iii) are of the common piezoelectric type. The first uses a cantilever strip or plate consisting of a bimorph crystal commonly of Rochelle Salt. The stiff spring and the reference mass here both reside in the cantilever itself. A typical sensitivity is 0·05 V per g for frequencies up to 2–3 kc/s, and accelerations down to some 0·001 g or less are measurable. In the second example shown the sensitive element is a plate of barium titanate with a metal reference block attached to one surface. This type may be usable up to frequencies of some 20 kc/s and accelerations of 10,000 g or more, with rather lower sensitivity than the above type. Accelerometers can usually be very light and robust. The piezoelectric type has a rather high output impedance and has a lower frequency limit, perhaps 10 c/s, set by the leakage resistance across it. These difficulties are avoided in the cantilever type by using a metal cantilever strip with a variable resistance strain-gauge bonded to it as the sensitive element. It should be emphasized that the vibration detectors described here are merely representative of the wide variety of practical types in common use. For a more detailed comparative discussion, Vigness (1957) may be consulted.

The amplifiers usable with vibration pick-ups are generally conventional. A useful

facility is a built-in electrical integrating or differentiating circuit, so that displacement, velocity and acceleration wave forms may be derived from a single pick-up.

Owing to the relatively low frequencies involved, frequency analysis of a vibration wave form usually requires a high-quality tunable filter of very narrow bandwidth, preferably of the constant-percentage-bandwidth type. In vibration wave forms pure-tone and random components are particularly prone to be combined, and the precautions necessary when analysing such mixed wave forms (see Dr. LITTLER's paper) are very important.

In observing transient wave forms, care must be taken that no important part of the frequency spectrum lies outside the working range of the pick-up or amplifier.

Calibration of pick-ups can be carried out on some form of vibration table using a microscope or optical interference method for standardization, or by the reciprocity technique (VIGNESS, 1957; HARRISON *et al.*, 1952).

2. ACCEPTABLE LEVELS OF VIBRATION

Our chief concern here is with the effect of vibration on human beings. The human body is a complex mechanical structure whose component parts vary very widely in stiffness, strength and density. If the body is subjected to vibration at a very low frequency, some 3 c/s or less, it moves virtually as a single unit and the adverse effects are essentially of the type associated with motion sickness. At higher frequencies, the various organs are displaced to varying degrees by the fluctuating forces which act on them. Heavy, lightly supported organs tend to be "left behind" in the motion, and so internal distortions are produced. Thus, for example, suppose that a layer of relatively soft tissue is located between a vibrating surface, which may be within or external to the body, and a hard, massive bony member as in Fig. 4 (*a*). The schematic diagram, Fig. 4 (*b*), is a spring of stiffness S (together with a damping element) attached to a mass M. A simple calculation shows that the peak acceleration in a sinusoidal vibration of the exciting surface required to produce a given peak compression of the tissue varies with frequency as indicated in Fig. 4 (*c*). It is constant at low frequencies, falling to a minimum where the spring and mass resonate with each other, and then rises at high frequencies. If the degree of compression of the tissue is taken as a measure of the effect perceived by the body, then the curve should indicate the acceleration level producing a given degree of human response.

Now while this model, or even the superposition of several such systems of differing resonance frequencies, is clearly a gross oversimplification, the results do appear to show some slight correspondence with subjective observations made on human sensitivity to vibration. Fig. 5 is a curve due to GOLDMAN (1957) summarizing various results for sensitivity for exposures of 5–20 min to sinusoidal vibrations variously applied. The accelerations are plotted for convenience as multiples of the gravitational acceleration, g. The curves do give some indication of a low-frequency plateau, middle-frequency minimum and high-frequency rise (cf. Fig. 4 *c*). Not too much weight should of course be attached to this, though resonances are known to occur in the body in the range above 5 c/s. Inasmuch as the variation of levels with frequency is tolerably small, having regard to the inevitable indeterminacy of such measurements, there is some justification for regarding the human body as an acceleration-sensitive device. It is premature to

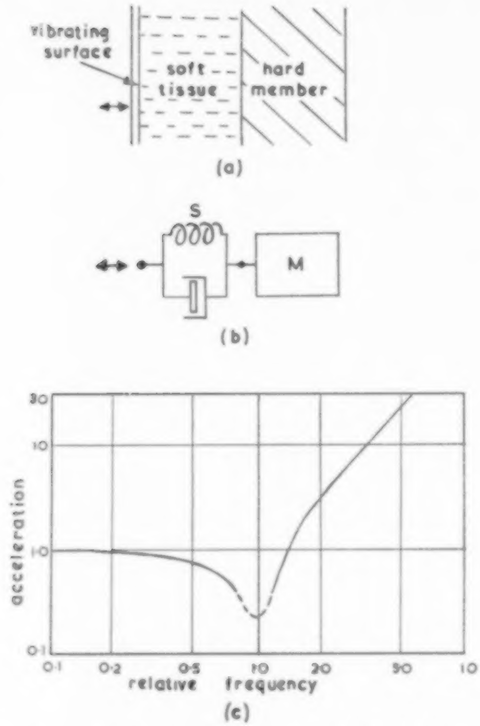

FIG. 4. A possible mechanism for vibration sensitivity in the human body. (*a*) System considered; (*b*) equivalent mechanical circuit; (*c*) resulting frequency curve of applied acceleration (arbitrary units) producing a given degree of compression in the layer of soft tissue.

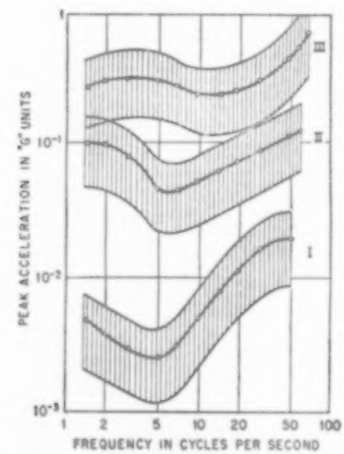

FIG. 5. Measured values of applied peak vibrational acceleration producing given responses in human subjects. Subjects find level I just perceptible, II unpleasant and III intolerable. (From GOLDMAN, 1957.)

claim that this would still be true for non-sinusoidal motions, but this is at least not unlikely.

Our knowledge of human tolerance of vibration is nevertheless still scanty, distinctly more so even than is the case for airborne noise, and the above curves are not to be interpreted too literally. Tolerance is, for example, doubtless considerably dependent on past exposure, duration, personal temperament and attitude to the source of the nuisance. GOLDMAN (1957) considers that accelerations up to 1 g below 20 c/s may be tolerated for periods of a few minutes: on the other hand, it is possible that vibration maintained over long periods, such as lorry drivers and air pilots are subjected to, may be more troublesome, particularly in regard to fatigue, than Fig. 5 indicates. No reliable quantitative information on long exposures appears to be available as yet, owing particularly to the difficulty of separating the effects of sustained vibration itself from the other kinds of mental and physical stresses which normally accompany exposure to it. A fuller discussion of human reactions is given by GOLDMAN (1957).

In normal peace-time conditions, human beings are rarely knowingly exposed to vibration levels likely to cause actual injury, the chief exception being in the use of hand-held industrial power tools, which are now well known as liable to cause damage to the hands, arms and shoulders. A common disease is the so-called "dead hand" or "white fingers", characterized by numbness and blanching of the fingers, with some loss of muscular control and reduction of sensitivity to heat, cold and pain. DART (1946) has summarized clinical findings and considered in particular the effects of modern tools which may run at high speeds of 10,000–50,000 rev/min (170–800 c/s). Damage can occur to the local vascular and nervous systems, the soft tissues, bones and joints. DART found that a delayed return of skin temperature of the hands to normal after chilling was a very simple and useful diagnostic indication of trouble due to vibration. He showed that the symptoms of certain very high-frequency vibrations (he estimated amplitudes of 0·003 in. at 12,000 rev/min, which corresponds to an acceleration of some 12 g) were significantly different from those of lower frequencies. Pain and increase in vascular tone, with few visible abnormalities apart from swelling, were more common than with "white fingers", which may be more characteristic of exposure to lower frequencies, say below 4000 rev/min. In particular, high frequencies produced symptoms much more quickly, in one case in a matter of days only, compared with months or years. It may be surmised that relatively small stiff structures like the hand and arm might have quite high resonance frequencies in their various parts and to connect a marked frequency selectivity with this. It would not appear impracticable to devise appropriate vibration-isolated grips for power tools, at least for the higher frequencies, and though there would be some penalty in cost, weight and working flexibility for the tool, the moral case for some such steps is surely a very strong one.

Vibration of buildings

Excessive vibration can cause cracking of masonry and plasterwork, though experience seems to show that only in exceptional cases is this problem likely to be serious. The U.S. Bureau of Mines showed that vibratory movements of the order of 0·1 in. are required to produce severe cracking of plaster. German work suggests that accelerations above 0·1 g are likely to cause building damage

(*Building Research Station Digest*, 1955). Thus it is generally likely that human beings will find the vibration conditions extremely unpleasant before there is serious danger to buildings.

Fatigue of metal

It is now well known that the maximum stress that a metal can withstand indefinitely without breaking is less if the stress is alternating than if static. Large vibrating stresses of magnitude safe statically cause small changes in the microscopic structure of the metal which may accumulate over perhaps some millions of reversals to the extent that fatigue cracks develop. Thus in the design of structures such as aircraft which are subject to powerful vibration, especially at high frequencies where a million reversals may be achieved in an hour, it is essential to avoid the development of large stresses by, for example, resonances in structural members. Much experimental work, normally carried out by means of resistance strain gauges attached to the structure, is being carried out on this problem but lies outside the scope of this paper.

3. ANTI-VIBRATION MEASURES

The measures available for minimizing the effects of vibration, as of noise, can be conveniently summarized under four headings:

3.1. *Planning*

This term is used to cover any essentially non-technical measures which may be possible to prevent the need for remedial steps arising. It includes such steps as the selection of machinery or processes for minimum vibration, the re-siting of existing machinery or of people disturbed by it, minimizing of the hours of exposure of personnel, and so on. Such measures hardly need further discussion.

3.2. *Reduction at Source*

Prevention is better than cure in this as in most fields, and since it is at their source that vibration and noise are most fully localized, preventive measures are often smaller in scope and therefore cheaper than others. Vibration in a machine frequently indicates wasted energy and undue wear, and its prevention is not necessarily inimical to the functioning of the machine. Such steps as dynamic balancing of rotating shafts, elimination of unnecessary impacts, soft padding or contouring of contact surfaces where transient pressures rather than violent blows are required, the inclination of stamping punch faces to smooth out the punching impulse, may be mentioned to exemplify this approach. Similar measures in any given case are usually fairly obvious.

3.3. *Absorption*

Insertion of absorbents in the surroundings of, or the transmission path between, source and observer: This technique, as distinct from those discussed in 3.4 below, is similar in principle to that discussed in Mr. FLEMING's paper for airborne noise but has so far been relatively little used in the case of vibration. It will probably increase in importance now that highly effective damping materials and resonators for coating (e.g. by spraying or adhesion) or attaching to metal structural members are available (OBERST *et al*., 1952, 1954; HAMME, 1957). With these it is possible by a light-weight coating to give a metal panel acoustic properties in many respects

similar to cardboard. Such coatings are very effective in preventing the drumming of metal panels excited into resonance by continuous vibration (e.g. in motor-car bodies). When absorbents are applied to a structure transmitting vibration in order to *attenuate* progressive waves (rather as absorbents are placed as linings within a ventilating duct), it is essential to remember that a considerable *length* of attenuating medium measured in the direction of propagation is usually necessary to produce a useful attenuation of the waves.

3.4. *Insertion of a Reflecting Barrier in the Transmission Path*

Vibration isolation

Since the vibrations of interest in practice are normally present in hard stiff solids, the most effective reflector is a soft elastic medium or element, typically the rubber or cork pad or the metal spring familiar as a vibration isolator.

Thus, consider a mass M (Fig. 6 *a*) to which a sinusoidal vertical force of amplitude F and frequency f is applied. M might represent a motor with an

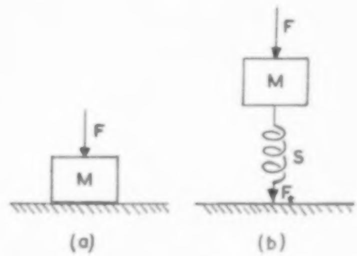

FIG. 6. Isolation of a vibrating mass. (*a*) Mass fixed to almost rigid floor; (*b*) mass on spring supports.

unbalanced shaft, say. If the mass is rigidly fixed to a stiff, heavy floor the full force F will be transmitted to the floor, which will vibrate slightly as a result. Now suppose that a spring of stiffness (i.e. tension per unit extension) S is interposed between mass and floor (Fig. *b*). Part of the force F will be required to overcome the inertia of the mass, and the rest to compress the spring dynamically. Only this latter component will now be transmitted to the floor. Denote it by F_t. A simple analysis shows that

$$\frac{F_t}{F} = \frac{f_0^2}{f_0^2 - f^2} \tag{4}$$

$$\text{where} \quad f_0 = \frac{1}{2\pi}\left(\frac{S}{M}\right)^{\frac{1}{2}} \tag{5}$$

and is the natural frequency of free vertical vibration of the mass on the spring. This quantity F_t/F is called the transmissibility, T, of the spring mounting system and $1/T$ is a measure of the effectiveness of the isolation obtained. T is plotted against frequency f in Fig. 7. It is seen that T is greater than unity, i.e. the spring has only an *adverse* effect, for frequencies less than about 1·4 f_0. For $f=f_0$ resonance occurs and the vibrating force is amplified to an extent limited only by the damping in the spring. The region of frequencies in which useful isolation is obtained thus begins well above f_0. In practice the vibration frequencies are

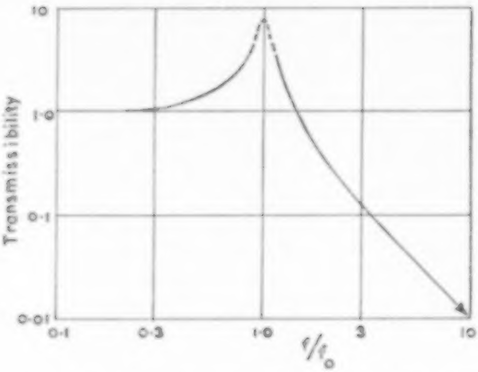

FIG. 7. Showing reduction of the force transmitted to, or the displacement produced in, the almost rigid floor due to spring mounting as in Fig. 6. Frequency is plotted relative to the natural frequency f_0 of the system.

given and it is necessary to use a sufficiently soft spring or to add sufficient mass to the motor to bring f_0 (equation (5)) well below the frequencies of excitation present in the system. When $f \gg f_0$ the isolation $1/T$ increases as the square of the frequency (equation (4)). The mass will cause a static compression of the spring through a distance d under gravity, given by

$$Mg = Sd$$

where g is the gravitational acceleration. Hence

$$f_0 = \frac{1}{2\pi}\left(\frac{S}{M}\right)^{\frac{1}{2}} = \frac{1}{2\pi}\left(\frac{g}{d}\right)^{\frac{1}{2}} \tag{6}$$

Thus, no matter what the physical nature of the springs*, the natural frequency f_0 and hence the isolation obtained are uniquely determined by the static deflection d. Corresponding values of f_0 and d from equation (6) are the following:

f_0 (per min)	6000	1200	600	300	120	60
(per sec)	100	20	10	5	2	1
d (in.)	0·001	0·025	0·1	0·4	2·5	10

It is immediately clear that the isolation of very slow-running machines requires springs of very great flexibility, which raises problems in locating the machine statically. Fortunately, the accelerations and dynamic forces produced in and by slow-running machines tend to be correspondingly small and so to present less of a problem.

The motion of the spring-mounted object under the exciting force also becomes relatively large if the mounting system comes into resonance. In fact a graph of the ratio of the peak amplitude of motion under a sinusoidal force to the static deflection under an equal but steady force, plotted against frequency, closely resembles Fig. 7.

The above simple theory assumes the foundation or base of the system to be

* Actually the assumptions that the stiffness S is linear and frequency-independent are tacitly made here. This, however, is usually not too far from the truth.

almost perfectly rigid. This is in practice rarely the case, even if the machine is mounted directly on, say, a concrete base on the subsoil. Resonances are commonly found in soil foundations (CROCKETT and HAMMOND, 1949) and decreased isolation will in general be obtained in such cases (SNOWDON, 1956). It is desirable to arrange for a fairly large isolation in the spring mounting at any frequencies at which such resonances may occur.

It should be clearly realized that the process here described is one of isolation rather than of absorption of the vibrational energy. Any damping present in the mounting spring plays only a secondary role: in fact it tends to reduce the high-frequency isolation, though usually not to a serious degree (SNOWDON, 1956), and some damping is desirable to reduce the resonant amplification near $f=f_0$.

The foregoing discussion supposes that the system has only a single degree of freedom: e.g. in this case the mass is assumed free to move only in the vertical direction. The theory applies exactly to any such case in which a single pure translation or rotation is involved, or to one where two or more degrees of freedom are present but are not coupled. When two degrees are uncoupled a static force on the spring-mounted system through its centre of gravity in the direction of one particular translational mode of vibration will produce a movement in that direction with no accompanying rotations. Fig. 8 (*b*) shows the coupled rotation caused by a

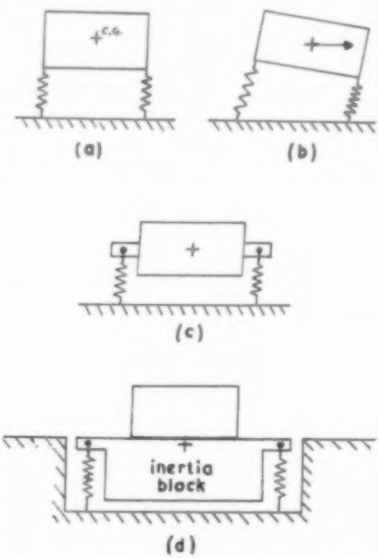

FIG. 8. Different modes of attachment of springs. (*a*) Beneath machine; (*b*) rotation of machine in case (*a*) by lateral force; (*c*) "centre of gravity" mounting which avoids rotational coupling; (*d*) added inertia block, giving increased mass and centre of gravity mounting.

horizontal force applied to a body mounted on springs beneath it. This rotation is avoided if the springs are attached at the level of the centre of gravity (Fig. 8 *c*). In the presence of coupling, the calculation of the natural frequencies and the isolation is considerably more complex, and in general the performance of an

isolator is likely to be adversely affected. While attachment of springs at the same level at the centre of gravity is not often practicable, the same effect may sometimes be obtained by mounting the body on a large inertia block of, say, concrete (Fig. 8 *d*). This has the additional advantages that the mere addition of mass reduces the amplitude of motion of the body under a given force, and permits the use of stiffer springs for the same natural frequencies, thus reducing the static mobility of the system.

Shock isolation

Exciting forces of an impulsive nature may be considered as the appropriate Fourier superposition of sinusoidal forces of various frequencies, and the same general conclusions as above will apply. Since there will now necessarily be exciting frequencies below the natural frequency of the system, there is now no critical limit below which this natural frequency must obviously be reduced. However, it is in general desirable that the natural period of the system $1/f_0$ should be considerably longer than the duration of any impulses of applied acceleration. A certain amount of damping is desirable to reduce the duration of the free vibration following an impulse, though strong damping of the viscous type can reduce the isolation itself.

One common fault in the practical application of isolation mountings is to leave relatively stiff connexions in the form of pipework, wiring, etc., between a sprung machine and its surroundings. For a full discussion of practical equipment and techniques see CREDE (1951, 1957). Other general works on vibration problems are HARTOG (1947)); Industrial Hygiene Foundation of America Inc. (1955); MACDUFF and CURRERI (1958); Schall and Schwingungen in Festkörpern (1956); TIMOSHENKO (1928).

Acknowledgment—The author is indebted to the U.S. Naval Medical Research Institute, and the McGraw-Hill Book Co. for permission to reproduce Fig. 5.

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THE APPLICATION OF CORRELATION TECHNIQUES IN NOISE ANALYSIS

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INTRODUCTION

FOR several years past, attention in noise analysis, and indeed in many branches of communication, has been concentrated on the frequency spectrum. The use of Fourier's theorem, and the development of analysers which permit the examination of a spectrum in different bands of frequencies, have been very fruitful; studies of the wave form—i.e. the time-pattern—of the noise have received little attention.

Recently, however, it has been realized that to look at noise problems in the "time domain" can lead to valuable results (LEE, 1950), and correlation techniques represent some of these (GOFF, 1955). The following is a highly-simplified account of some ways in which results can be obtained in noise analysis, which are difficult or impossible by conventional means. While there is no space for details, it is hoped that descriptions of the methods will be interesting to some who are working on these problems, and show them the advantages which, in many cases, the correlator can give.

THE PHYSICAL EXPRESSION OF CORRELATION

As an introduction to the idea of correlation, let us assume that a large multiple store in a manufacturing city wishes to have some idea how to forecast its sales.

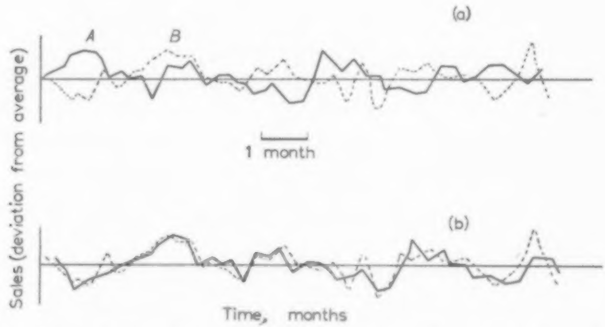

FIG. 1. (*a*) Sales of minor items (*A*) and major items (*B*) as a function of time.
(*b*) As (*a*), but curve *A* delayed by 2 months.

When two graphs are plotted, as shown in Fig. 1 (*a*), of sales of minor items and consumable goods at A, and major items (furniture, large electrical appliances, etc.) at B, there appears to be no resemblance between the two sales-patterns. While each

is presumably affected by the fluctuating prosperity of the city, there is no correlation between them.

Let us, however, suppose that we delay curve A by 2 months, as in Fig. 1 (*b*). The two now show a high degree of similarity. The inference is that a slump in buying of ordinary consumer items is followed 2 months later by a slump in major items, and vice versa. When conditions worsen economically, people evidently stop spending on smaller items, but are committed to, or make an extra effort in buying, the larger ones; when conditions improve, they immediately make up on smaller purchases, but wait to be sure of the improvement before making major purchases.

How was this figure of 2 months arrived at? The method is as follows. To find the resemblance between two curves we may multiply them together and take the average product. If this is done for the curves of Fig. 1, we have the result shown in Fig. 2 (*a*). The long-time average is zero, because any product at any one ordinate is as likely to be positive as negative; this is in fact what we mean by their being "uncorrelated".

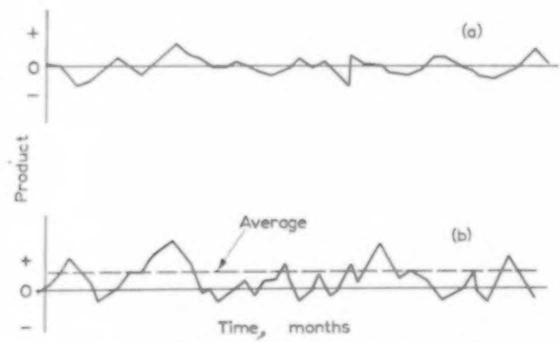

Fig. 2. (*a*) Product of curves *A* and *B* in Fig. 1 (*a*): long-time average zero. (*b*) Product of curves *A* and *B* in Fig. 1 (*b*): long-time average positive.

If we shift one curve by one week and go through the same procedure, we might get a similar result. But by the time the shift had come to two months, the product curve would look like Fig. 2 (*b*), with a long-time average shown by the dotted line.

We could now plot a curve showing this long-time average product as a function

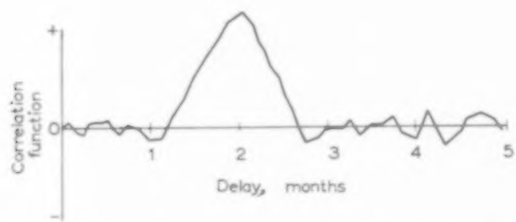

Fig. 3. Cross-correlation function of curves *A* and *B* in Fig. 1, shown as a function of the delay.

of delay, as in Fig. 3. This curve is known as the *cross-correlation function* between the two variables.

We have arrived, in this descriptive way, at the mathematical equation

$$\phi(\tau) = \underset{T\to\infty}{\text{limit}} \frac{1}{T}\int_0^T f_1(t) \,.\, f_2(t-\tau) \,.\, dt$$

Here $f_1(t)$ and $f_2(t)$ are the random functions, varying with time, under investigation; one is delayed by τ, the two are multiplied together, integrated and averaged over T, which should be in practice as long as possible. This process gives the correlation function $\phi(\tau)$, which is a function of the delay.

DESIGN OF AN ELECTRONIC CORRELATOR

Practical instruments are of several types, but all carry out precisely these operations (Fig. 4). The two functions of time for the inputs are represented by the random noises picked up by two microphones. The delay may be produced by recording one noise on a tape loop and replaying after a short delay. The product is formed in some type of multiplying circuit, while the averager may be a simple

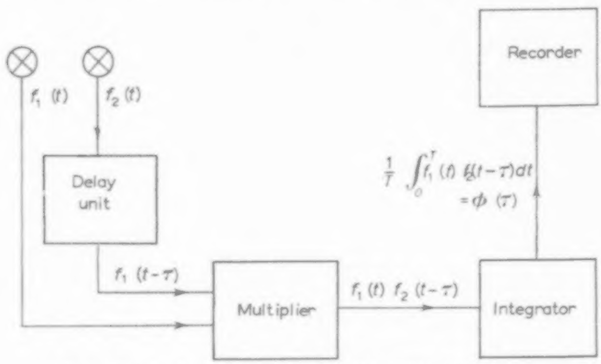

FIG. 4. Block diagram of an electronic correlator.

RC circuit with a long time-constant. The output of this, which is the correlation function, can be recorded by a recording milliammeter if at the same time the delay is slowly increased.

One great advantage of the correlator is that the two channels—microphones, amplifiers, etc.—may have any frequency or phase characteristics, provided only that they are identical; uniform response with frequency is not necessary.

The requirements for performance of certain components, particularly the time-delay and multiplier, are quite stringent if low signal/noise ratios are to be handled. As this paper is concerned with applications, however, no design data are given. We will assume that we have a functioning correlator to apply to our tasks.

APPLICATION OF CORRELATION TECHNIQUES

1. *Location of noise sources*

This application exemplifies closely the technique given in the introduction, and at the same time enables a problem to be solved which is very difficult by conventional acoustical techniques. Let us assume that we wish to reduce the noise inside

the control room of a power house (Fig. 5) and we have to determine which of the several machines is the chief contributor. If the different noises they make are

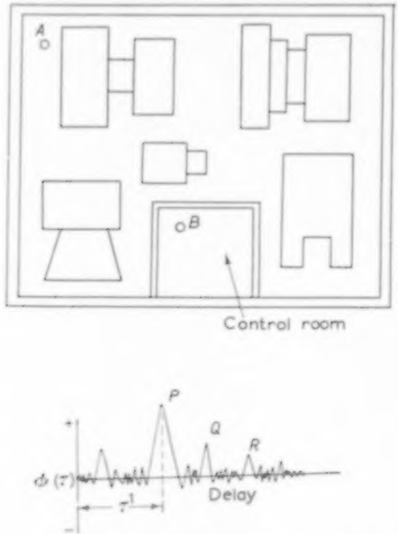

FIG. 5. Diagram of power house, and cross-correlation function of outputs from microphones *A* and *B*.

distinctive, there would not be much of a problem; but it is frequently the case that their spectra are very similar. Such cases usually need experienced judgment, coupled with lengthy testing.

Suppose we set up a microphone A so near to one machine that it picks up essentially only the sound of that particular machine, and another microphone B in the control room, and cross-correlate their outputs. In general the noise arriving at the two microphones will be completely uncorrelated, and the instrument will not give much output. At a value of delay say τ', equal to that undergone by the sound wave in travelling from A to B, the delayed input of microphone B to the multiplier will have a component identical with that of microphone A; these two will give a positive correlation as at P. (There are of course components due to the noise from other machines in the outputs of A and B, but they will be incoherent, so their long-time average will be zero.) As the delay increases, we may have subsidiary peaks as at Q, R, etc., due to sound waves passing A and then reaching B by reflection from, say, the rear wall; but, due to the appropriate delay time, the correct peak may easily be identified, and the proportion of the noise reaching B which originated at A may be found from its height.

It may be objected that this result could have been obtained very easily by shutting off all machines except one. This is of course true; but is frequently quite impossible to do in practice. Further, one sometimes has a problem such as the contribution of different parts of the jet from a jet engine to the noise at a point; here it is quite impossible to have only one "source".

2. *Reduction in wind noise*

If we are trying to measure, say, the level of noise on the ground due to an aeroplane flying overhead, and a strong wind is blowing, the noise of the wind over the microphone might well mask the noise of the aircraft. As the noise is random and of a similar nature to aircraft noise, it is virtually impossible to separate them.

The wind noise is due largely to eddies, which are of course finite in size. This means that two microphones separated by a few feet will be acted on at any moment by different eddies, and thus the outputs of the two microphones due to wind noise will be incoherent; the noise from the aircraft, however, will be the same in each. If we cross-correlate the two outputs, only the aircraft noise will contribute to the correlation function; the wind noises, even though they may be quite large, will be incoherent and so average out to zero. An increase in signal/noise ratio of over 20 dB can be easily obtained, and for this application no delay unit is needed.

The choice of separation is important. If the microphones are too close, the wind noises will become coherent, leading to error; if they are too widely separated, directional effects will appear, as the aircraft noise may not reach the microphones exactly in phase. (This directional property can in fact be used, as will be discussed later.)

3. *Acoustic attenuation of panels*

This is an investigation which normally demands two heavily constructed rooms, often on separate foundations, between which the panel is very carefully sealed in

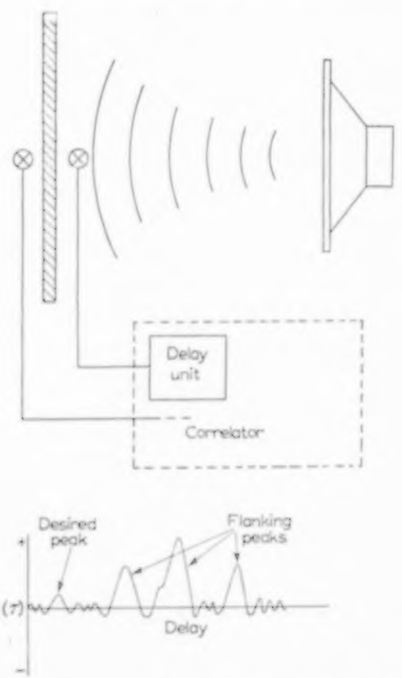

FIG. 6. Block diagram of arrangement for panel testing, and correlation function.

position. One room contains the noise source and the other contains the microphone, and these extreme precautions are necessary to ensure that the sound reaching the microphone has all passed through the panel, and flanking sound has been completely eliminated.

For this reason, the correlator method, in which a panel a few feet square is supported in the middle of an ordinary room, with a microphone on each side of it, looks fantastic (Fig. 6). But if the source is random noise, and the microphone outputs are cross-correlated, the result will be as shown; at a value of delay corresponding to the sound travelling through the panel, there will be a peak in the correlation function. There will of course be much larger peaks due to sound which has passed around the panel, but these will occur later, and thus should be distinguishable.

This method is clearly very similar to panel testing using pulse techniques. In this a sharp pulse of sound is emitted by the loudspeaker and picked up on the two sides of the panel; flanking sound again arrives later and may be separated. The correlator used in this way shows similar properties to a time filter, and this is to some extent a consequence of working in the time domain rather than the frequency domain. The correlator has the advantage that the sound source is used continuously at low power, instead of occasionally with high powers; not only are non-linear effects thus avoided, but any noise source—say, a machine, or ventilating grille—may be used.

We usually need to know the attenuation of the panel as a function of frequency. A difficulty immediately arises, however, if we limit the bandwidth of the noise source; it will be shown in the next section that for band-limited noise the correlation function spreads out. This would mean that, on the record, the peaks due to flanking would interfere with the one we want. (Pulse methods have an exactly similar limitation.) The only way of dealing with this is to use a larger panel, to increase the delay of the flanking noise.

In practice the use of a 1/3 octave bandwidth analyser is feasible; for technical reasons the choice of the channel to insert the filter in is of importance. The whole problem is by no means a simple one, but the correlation method has several advantages; not only are the usual massively constructed rooms unnecessary, but the panel may be tested in a variety of ways other than with the edges clamped.

An exactly similar method can be used for testing acoustic absorbing material; in this case unwanted sound arrives *before* the wanted signal, and filtering and allied problems are different.

SPECTRUM WIDTH AND CORRELATION FUNCTION

Let us look at the correlation of two identical functions, a process called *autocorrelation*. If we have noise covering a wide spectrum it will vary rapidly with time, as in Fig. 7 (*a*), and it is clear that for even a small delay the two functions will be so dissimilar that the long-time average product will be zero. The autocorrelation function will thus fall to zero very rapidly, as shown.

If the noise is band-limited—i.e. has a restricted frequency range, as in Fig. 7 (*b*) —there is less dissimilarity between the two functions for small delays, and we have an autocorrelation function more as shown. In both these cases, the first zero occurs at a delay given approximately by 1/(highest frequency present).

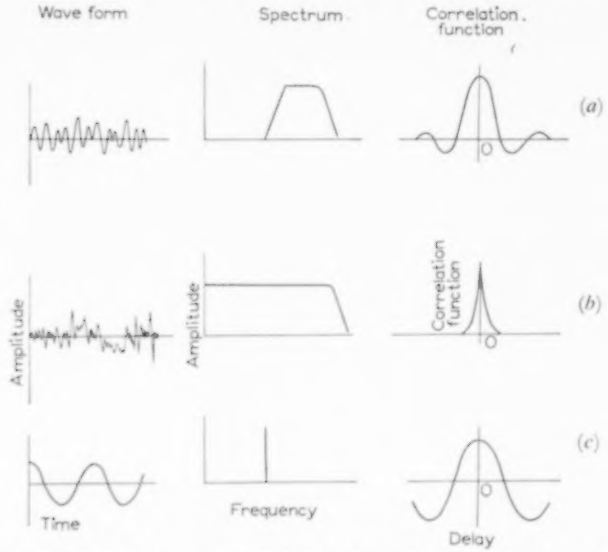

FIG. 7. Relation between wave form, spectrum and autocorrelation function. (*a*) Wide-band noise; (*b*) band-limited noise; (*c*) sine wave.

Supposing, however, we go to the narrowest spectrum, i.e. a sine wave (Fig. 7 *c*). Since a sine wave exactly repeats once per cycle, the autocorrelation function will repeat exactly too.

We see here a most important conclusion: the spread of the autocorrelation function is inversely proportional to the spread of the spectrum. We will show how this fact can be used.

DETECTION OF A SINE WAVE IN NOISE

We now turn to a problem which hinges on the difference between the autocorrelation function of a sine wave and of random noise. Suppose we wish to filter out a very weak sine wave from noise spread over the audio-frequency band. If we autocorrelate for a sufficiently long delay (Fig. 8), the autocorrelation function of the noise will drop to zero, and a periodic part will be left, representing the sine wave. A sine wave some 30 dB below noise can easily be detected.

It may be pointed out that a filter of bandwidth 4 c/s (as in a commercial heterodyne analyser) will do this as well. The great disadvantage of filtering, however, is that if the signal alters in frequency, it goes off the pass-band of the filter, which will need retuning; or if the frequency is unknown, the whole audio bandwidth must be slowly searched to find it. The correlator, however, may have a bandwidth of some octaves, and can deal immediately with any signal in this range, or with a signal varying in frequency.

The advantage of the correlator in this respect may be understood on an "information" basis. The filter discards all the information in the signal except that lying within its pass-band; the correlator is, however, using all the information in the signal all the time, and so would be expected to be faster.

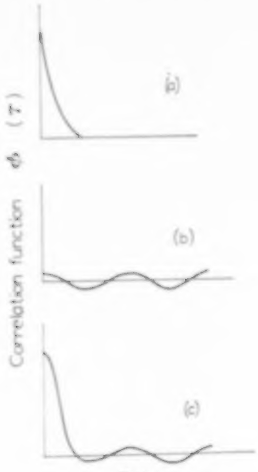

FIG. 8. Autocorrelation function of (*a*) wide-band noise, (*b*) sine wave, (*c*) sine wave in noise.

If the frequency of a signal is known, and it is required to know whether it is present or not in a sample of noise, the noise may be cross-correlated with a signal of the same frequency. Quite startling improvements in signal/noise ratio can be obtained in this way; a signal more than 40 dB below noise can be detected, and the method is applicable to other periodic wave forms as well.

A rather similar application is to the examination of noise for very low frequencies. Conventional filters in the range of 1 c/s are very bulky and complex. But if we examine a correlation function for a delay of several seconds, periodicities of this order are readily perceptible.

In general the correlator is at its best in dealing with wide-band noise. Certain applications such as noise source location and panel testing would be impossible with pure tones, but they may be used in certain circumstances. We may, for instance, be trying to find whether the inner or outer propellers of a four-engined aircraft contributed more to the cabin noise at high speed—a restriction which precludes taking measurements first on one pair of engines and then on the other.

This may be done by placing one microphone near one propeller and the other in the cabin, and cross-correlating their outputs. To reject the contribution of the other propeller to the microphone in the cabin, we need to alter its speed slightly and use a long integration time. In practice a difference in speed of about 1 rev/min may be all that is needed. The correlator in this case acts as a series of heterodyne analysers, with i.f. frequency of zero, and bandwidths of the order of 1/(integration time) whose centre frequencies automatically "track" those of the input; i.e. the engine can fluctuate in speed without upsetting the operation, giving again an advantage over filtering.

MISCELLANEOUS APPLICATIONS

It can be proved that the cross-correlation of input and output of a device, for a wide-band source, gives the impulse response of that device. This provides a means

of testing, say, an acoustic filter for impulse response. On a different scale, the impulse response of an aircraft or other structure may be carried out without using impacts by driving a vibrator with random noise, using a pick-up at the desired point, and cross-correlating the two signals.

The method of noise source localization, mentioned above, may be applied to finding the path taken by vibration from one point to the other in a complex structure. The peaks in the cross-correlation function between signals picked up at the two points will indicate the delay time (or times, if there is more than one peak), and examination of the structure, knowing the speed of sound in different parts, should give the appropriate paths.

In the section on microphone wind noise it was stated that two microphones, separated by an appreciable distance, will behave as a directional microphone. By using more elaborate arrays, and by using different delay times, a highly-directional unit may be obtained.

A rotating, two-microphone array may be applied to determine how diffuse is the sound field in a room, a property which may have some bearing on its acoustic qualities. If the sound is perfectly diffuse, i.e. travelling with equal energy in all directions, there will be no change in the cross-correlated output of the microphones (with delay corresponding to the acoustic path difference between them) as they are rotated; but if the sound field is directional, the variation of the cross-correlation function will indicate it.

HIGH-SPEED CORRELATION

Most correlators scan the delay rather slowly, at, say 1 msec/min, and so take some time to deal with the information coming to them. One type of instrument has been developed which can display correlation functions immediately and continuously, losing no information from the signal. It is a complex device, using pulses in the 30 Mc/s region, but may have an important application in special cases.

CONCLUSION

The foregoing has been a very brief and unmathematical description of some uses of the correlator. In every case quoted, and in many more applications, a great deal more could have been written, but it is hoped that the reader has become familiarized with the underlying ideas. In the writer's view, these techniques are most exciting and promising, and it may be no exaggeration to say that they are adding a new dimension to the methods of noise analysis.

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A STUDY ON OCCUPATIONAL DEAFNESS IN THE NETHERLANDS

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INTRODUCTION

Noticing much deafness among our shipyard workers, we have started an investigation on the frequency and the severity of noise damage in several groups of workers in different kinds of departments with a high noise level at factories covered by the Industrial Health Service, Dordrecht, Holland.

TECHNIQUE

The method of continuous audiometry (van Dishoeck, 1948) was used for the determination of auditory thresholds because of its speed, accuracy and superiority in finding small local hearing losses.

In continuous audiometry it is not the intensity that is varied to find the hearing threshold for one frequency at a time (as is usual in octave audiometry), but frequency is varied to find which frequencies are heard and which are not heard at a given intensity. By changing intensity levels a complete audiogram is made in a much shorter time than is possible by the ordinary octave method and more particularly so with the typical dip of noise trauma. The place and thus the magnitude of its maximum, the extension into the lower (speech) frequencies and, for differential diagnosis, the lesser degree of loss in higher frequencies are quickly and easily measured.

The Peekel audiometer has a continuously variable frequency between 80 c/s and 12,000 c/s and its intensity output is adjusted to the normal auditory threshold; during the sweep through the frequency range the intensity of all frequencies from 200–8000 c/s stays uniform in dB above their respective normal thresholds, which makes this audiometer ideal for screening.

The average error in continuous audiometry was the same as, or smaller than, in octave audiometry (van der Waal, 1955). The continuous audiometer gives more accurate and more detailed information in less time.

MATERIAL

Sound pressure levels were measured by the Research Institute for Public Health Engineering T.N.O. with the Technical Physics Department T.N.O. and T.H. and by the Institute of Preventive Medicine in a dozen departments with more or less heavy noise of 7 different factories. About 300 audiograms, taken from employees working there, were analysed. Audiograms of people with a history of suppuration of the ear or evident exposure to a higher noise level than in their present function were excluded from this analysis.

EXAMINATION ROOM

The results of audiometry are highly influenced by the level and quality of the background noise in the examination room. In factories even the quietest room is not comparable to the specially built silent rooms of an E.N.T. clinic. However, bringing the labourers to the institute is not convenient in most cases and thus the audiometer must be taken to the labourers. When doing this, the examiner, finding threshold anomalies, must know what part of the measured hearing loss is due to masking by background noise and what part can be attributed to acoustic damage.

The hearing threshold of a normal subject was proved to be disturbed by a background noise level of 20 dB and more. Using telephones with rubber cushions that give 10–20 dB reduction, the acceptable noise level in any examination room is 30–40 dB, which is a stringent demand for industrial circumstances. Most often this level can be attained for high tones by simple noise insulation measures, but for low tones it is more difficult and for them the unavoidable level is higher than would be acceptable and a disturbance of the audiogram must be reckoned with. By establishing the threshold-shift of normal people under these circumstances, a reference value for pathological audiograms is obtained. Hearing losses as large as, or smaller than, this threshold-shift cannot be measured.

For our investigation the reference threshold curve used was the average audiogram of twenty persons 15–25 years of age, without evidence or history of hearing damage, taken in an examination room that amply met the above-mentioned requirements. Above 1000 c/s this curve is in good accordance with those of DADSON and KING (1952) and of WHEELER and DICKSON (1952). Under 1000 c/s a deviation, simulating hearing loss, is present, apparently as a result of low-pitched background noise. But the mean threshold curve of the investigator was the same both under these conditions and in a silent audiometry room of the Leyden E.N.T. clinic. This suggests that the above-mentioned effect is not real masking but due to inexperience of the tested employees to distinguish low audiometer tones from background noise. This same disturbance has been found by KREJCI and BORNSCHEIN (1951) and COX *et al.* (1953), but it cannot be attributed to acoustic trauma as the former did.

LABORATORY EXPERIMENTS

As an extension of a series of laboratory experiments by VAN DISHOECK (1948) and VAN GOOL (1952) on auditory fatigue after stimulation with pure tones, we studied the effects of 5 min exposure to white noise, to recorded industrial noise and to octave-band noise. Octave-band noise was found to have the same fatiguing properties as have pure tones, in respect of the relation between frequency of the stimulus and frequency of the threshold-shift. Wide-band noise caused more threshold-shift when the amount of low tones was less, the total sound level being the same. In these experiments with short exposures to loud tones or white noise the values of maximal threshold-shift did not show bimodal distribution. No distinct separation but a gradual change from noise-susceptible to non-noise-susceptible individuals was found.

INDUSTRIAL STUDY

In order to study the correlation between industrial noise level and resulting hearing loss, three methods were developed to determine the amount of acoustic

damage present in every group of employees working under the same noise conditions.

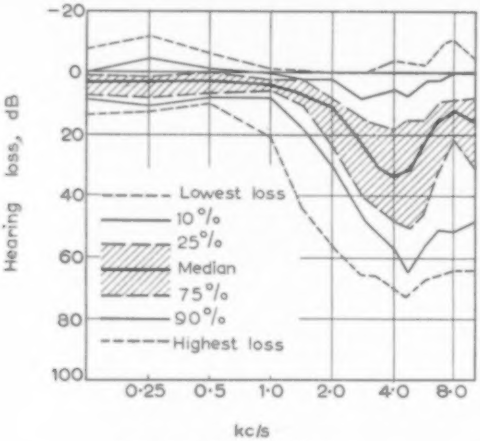

FIG. 1. Group-audiogram.

1. *The group-audiogram* (Fig. 1)

This gives the percentage distribution of hearing losses in decibels at a selection of frequencies for each group of workers. In our case hearing losses were read from the continuous audiograms at 0·125, 0·25, 0·5, 1·0, 1·4, 2·0, 2·8, 3·3, 4·0, 4·8, 5·7, 6·7, 8·0 and 10·0 kc/s. From all audiograms in a group the hearing loss values at a given frequency were put in order of magnitude. The smallest (0 per cent), the largest (100 per cent) and median (50 per cent) value and in addition those for 10, 25, 75 and 90 per cent were calculated, recorded in an audiogram blank and connected to a curve with the corresponding points from the other frequencies. The median band (the middle 50 per cent of the values, between the 25 and 75 per cent curve) or the median (50 per cent) curve alone of the different groups can be compared and a sequence according to traumatic involvement arranged.

2. *Statistical calculation of significant differences in hearing loss values at a given frequency between noise groups or between noise and non-noise groups*

Though these computations can be made for all the above-mentioned frequencies, calculations can be simplified by reducing the audiogram to four values as follows:

(*a*) The median of hearing loss values at 125, 250 and 500 c/s.

(*b*) The hearing loss at 1500 c/s, which is the lowest possible frequency under which hearing should be intact to enable a reasonably good understanding of speech.

(*c*) The maximal hearing loss in the 2000–6000 c/s region; except that from sharp, tapering dips, the part narrower than ¼ octave is neglected to avoid including incidental narrow dips caused by resonance in the ear canal or the telephone.

(*d*) The smallest hearing loss above 6000 c/s.

Moreover, we need

(*e*) Conformity of air- and bone-conduction audiograms.

(*a*), (*d*) and (*e*) are mainly of value for differential diagnosis. If the hearing losses at low and high frequencies are small and there is no difference between air- and bone-conduction audiograms, then most often a pure acoustic trauma is present. If they are large, another kind of deafness must usually be considered.

Contrary to these values, which indicate the purity, (*b*) and (*c*) indicate the severity of the noise damage and the menace to comprehension.

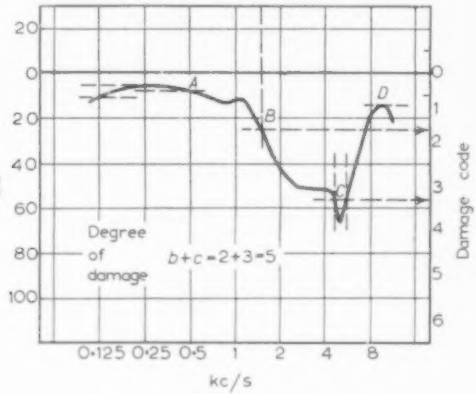

FIG. 2. Degree of damage.

3. *The degree of damage*

We coded both values (*b*) and (*c*) (Fig. 2) and joined these ciphers by simple addition into one "degree of damage" for each individual ear (see Table 1). Thus we took into consideration both the depth and the width of the typical noise dip (Fig. 3).

TABLE 1. HEARING-LOSS CODE FOR CALCULATING THE DEGREE OF DAMAGE

Hearing loss (dB)	Code	
Less than 10	0	(normal)
10–19	1	(indication of loss)
20–39	2	(definite loss)
40–59	3	(medium loss)
60–79	4	(serious loss)
80–99	5	(heavy loss)
100 and over	6	(useless rest)

When putting the departments in a sequence according to the percentage distribution of the degree of damage or according to the shape of the median 50 per cent band of the group-audiogram, we can compare this sequence with the one that results from arranging them according to their noise spectra by criteria as given

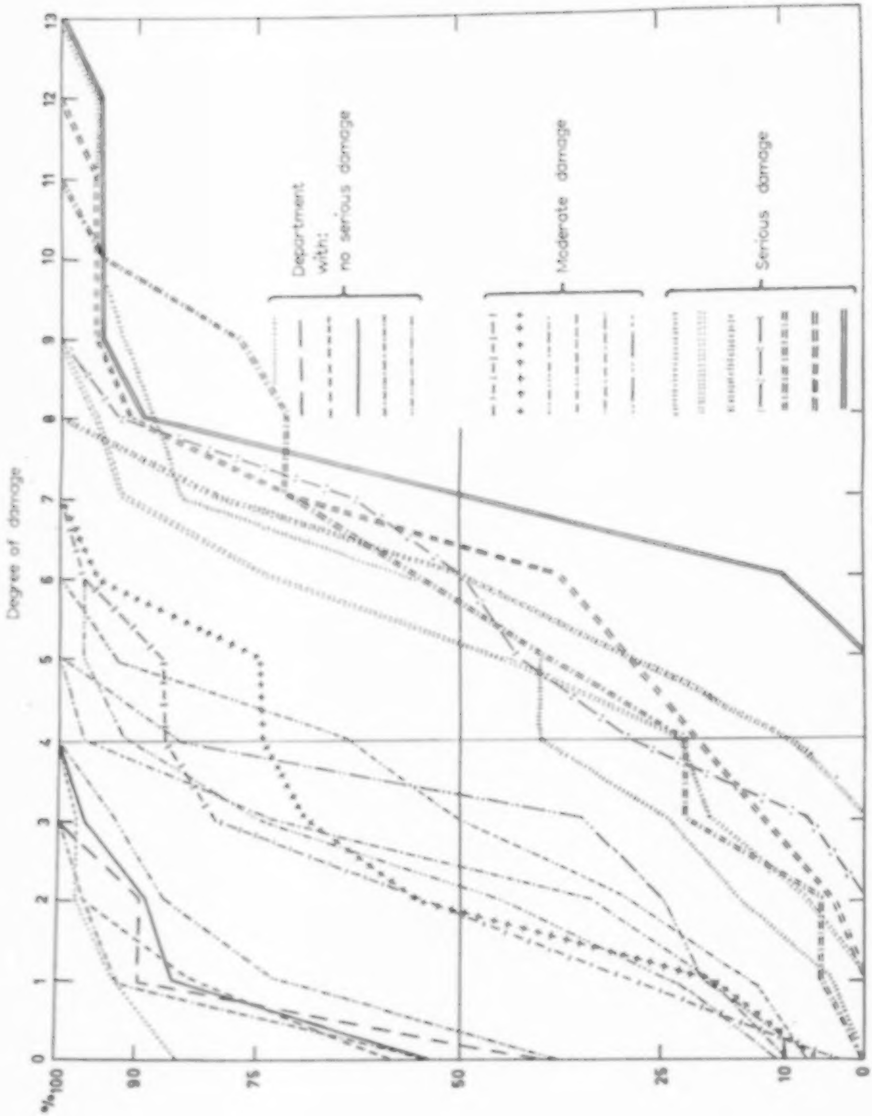

FIG. 3. Cumulative curves of the percentage distribution of the degrees of damage for several different departments. The percentage of cars that has the horizontally indicated degree of damage, or less, is shown on the vertical scale.

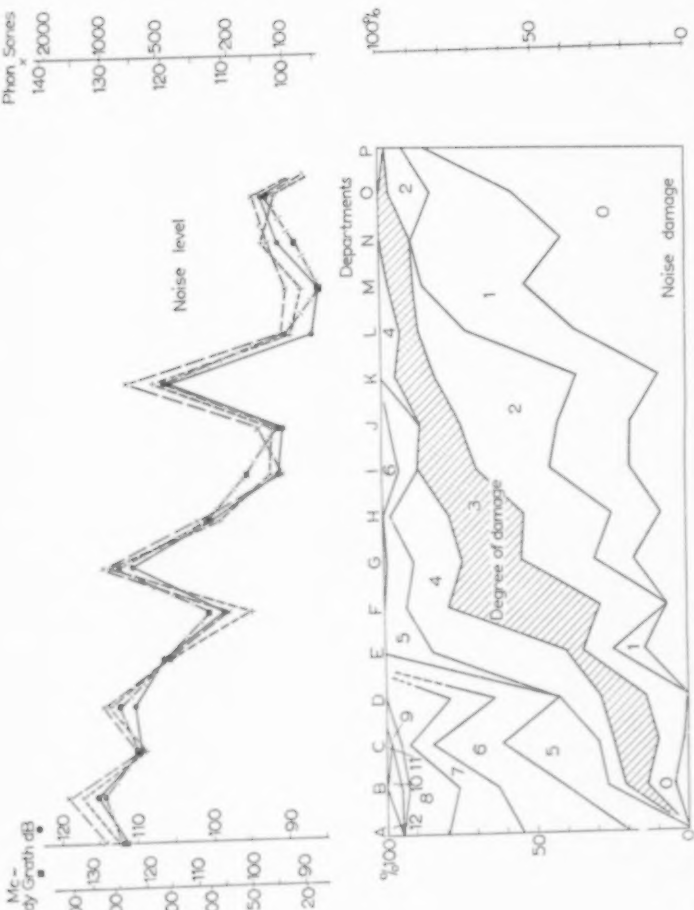

FIG. 4. Mutual comparison between noise criteria and audiometric data. In departments G and K the measured noise level was present during relatively short periods and ear defenders were worn by many of the workers.

by KRYTER (1950), MCGRATH (1952), HARDY (1953) and others. This gives an opportunity for mutual comparison between audiometric data and noise criteria and tests merit and usefulness of the applied methods. In our cases of the usual rather flat industrial noise spectra, good accordance was found for all noise criteria (Fig. 4).

It is clear that a positive correlation exists between the average hearing loss per group and noise spectrum level. The critical noise level above which definite trauma is present in our material is about 90 dB total level, 150 sones total level, 35 sones maximal in one octave band (HARDY, 1953) McGrath-code 10. The group-audiograms indicate that to a certain noise level a certain average hearing loss belongs. Probably the amount of hearing loss after some months' exposure does not depend on the duration of exposure, but mainly on the noise level to which the worker is exposed. If this is true, it means that in a relatively short time a trauma is acquired as large as corresponds to the noise level and that thereafter, from this cause, the hearing loss does not increase. New damage may occur when the employee shifts work to a department with a higher noise level. When in course of time presbycusis develops, hearing loss from this cause most probably is added to the existing noise damage. From our data we may conclude that most of the ultimate hearing loss is produced in the first year of the noise exposure. The gradual increase in later years largely depends on this presbycusis.

Of special interest was the comparison between audiograms taken before and after a day's work. From the percentage distribution of the degree of damage for the different departments before and after work, it was evident that there was a shift to the larger degrees of damage during exposure. This shift was more pronounced in departments where many workers with less than 3 months' exposure were employed. Separating the "juniors" from the "seniors" proved that the latter, their trauma being definitive, show only small daily changes in auditory threshold (5 dB or less). The unaccustomed "juniors" show much larger differences, so that after a day's work the average hearing losses of both groups attain a pretty good resemblance to each other. Thus the evening audiogram of a young labourer foreshadows the permanent damage he will have later, when he continues to work in the same noise. This might be a method of determining the individual sensitivity to noise trauma.

The presumption that older people are more susceptible to hearing damage than younger could not be verified from our data. A slight indication is present only for audiograms of persons working in noise for more than 8 or 10 years.

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AUDITORY DAMAGE IN YOUNG MEN AFTER SHORT EXPOSURE TO INDUSTRIAL NOISE

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INTRODUCTION

As part of a recent investigation conducted for the Royal Naval Personnel Research Committee of the Medical Research Council into the hearing of certain noise-exposed men of the Royal Navy, it was necessary to obtain comparable data from a typical group on enlistment into the Service. The total number of young recruits examined was 111, and an analysis of their hearing state in relation to their estimated exposure to noise during the time between leaving school and entering the Navy was thought to be of interest as a rough indication of present trends within the population as a whole.

METHOD

The men were examined individually by an otologist and a physicist who tested the hearing with a commercial pure tone audiometer using a conventional technique in an extremely quiet room. The audiometer, in common with most others now in use in Great Britain, was calibrated by the manufacturer to American standard normal threshold (American Standard Z24.5, 1951) and employed an attenuator giving intensity steps of 5 dB for assessing hearing loss. It has long been recognized that the American thresholds are too loud so that it is often found that young, normally-hearing subjects respond to tones of the minimum intensity available from the audiometer, i.e. tones 10 dB weaker than the American threshold; or −10 dB, a hearing "gain". For this survey a 20 dB matched pad was inserted between the audiometer and the telephone receivers to enable more acute hearing to be assessed accurately.

A British standard normal threshold has lately been adopted (British Standard 2497), 1954) which is somewhat quieter than the American but still remains to be validated as regards its applicability to field studies using clinical audiometers. The thresholds taken as British standard were obtained in laboratory studies using apparatus which included atenuators with 2 dB steps and with subjects screened by preliminary audiometry. Thus, differences due to practice afforded by this first audiogram and to the finer step of the attenuator were factors expected to contribute to a quieter threshold than that obtained in field work on normally hearing subjects. As it was known that the noise-exposed men had no more than a slight average hearing loss, to determine its exact extent it was essential to test under identical

conditions a control group of new entries, rather than use a relatively uncertain standard threshold.

RESULTS

On classifying the men according to the noisiness of their occupations, the resulting distribution was:

From jobs in industries where a noise hazard possibly existed, e.g. coal mining, shipyards, forges, machinery of noisy type ...	81 men
From relatively quiet work, e.g. offices, shops, *quiet* farming, etc. ...	25 men
Direct from School	5 men
	111

Men with a history of work in extremely noisy surroundings (10 per cent) were excluded without reference to the audiometric findings. Also excluded were those (9 per cent) with more than a fixed criterion of gunfire exposure (mainly Army Cadet Force and others who had fired shot-guns), those with minor ear pathology (5 per cent) and one subject each with ear-drum perforation, history of fractured skull involving the ear, and severe perceptive deafness of non-industrial pattern. This left a control group of 73 per cent of the recruits examined whose average age was 17·7 years. Usual audiological practice was followed in expressing thresholds for the group in terms of the median value with lower and upper quartiles; these were calculated for a range of 8 test frequencies (250–8000 c/s) treating left and right ears together.

After excluding from the control group all those who had fired 8 or more rounds from small arms (including even the 0·22 in. rifle), there remained 15 per cent of the total who could be considered otologically pure. The median threshold of this restricted sample was also computed as a check on the control group as a whole. Averaged over the 7 lower test frequencies, the otologically pure group had more acute hearing by only 0·4 dB though at the eighth test point, 8000 c/s, their hearing was better by 3·0 dB.

Calculation of the modal values of the thresholds of the main control group for comparison with the British standard figures (given only in terms of modal values) showed very good agreement at 250 and 8000 c/s, and at intermediate frequencies the hearing of these subjects approximated to midway between the British and American standards.

The 10 per cent who had been exposed to extremely noisy working conditions were of similar age (average 18·8 years) to those used as controls and therefore no question of a correction for presbycusis arose. As expected from the known general character of industrial hearing losses, the maximum divergence between the median thresholds of these men and the control group occurred in the form of a 4000 c/s "notch" and amounted to 6·4 dB. At 4000 c/s the interquartile range was 18·6 dB compared with 9·2 dB for the controls.

Here, for the purpose of illustration, the level of zero hearing loss corresponding to the British Standard has been adopted. That a certain indifference to the use of the British Standard exists is indicated by the fact that the following figures are believed to be some of the first clinical audiograms published in which hearing losses are referred to this reference level. Fig. 1 shows the audiograms of three of

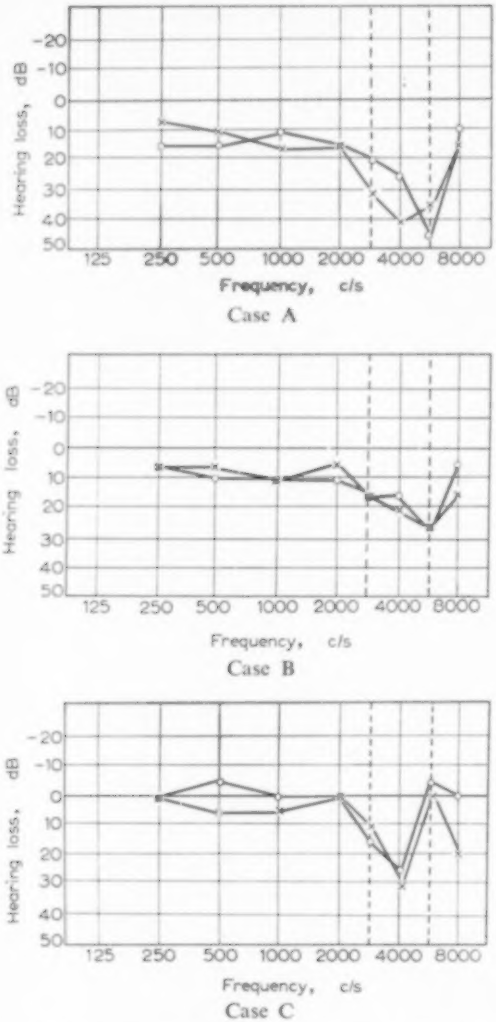


Fig. 1. Audiograms of 3 cases of industrial acoustic trauma.
Air conduction: right ○—○—○
left ×—×—×
Instrument make: Amplivox, Model 61, Serial No. 298.
Corrected to British Standard normal thresholds.
Recorder: J. J. K., February 1958.

these men who had been exposed to industrial noises. Details relating to the men instanced are as follows:

Case A

Aged 16 years, 6 months.
Fired nothing larger than an air-rifle.
Industrial noise-exposure:

School metal-work classes—panel-beating, forging, etc. Course lasted 6 weeks. Dullness of hearing and tinnitus for seconds only.

Various employments—lorry driver; frying noises in a potato-crisp factory; noise of handing steel crates in a brewery. All of short duration, "not very noisy" and with no temporary deafness or tinnitus noted.

Lawnmower-motor mechanic for 1 year. Very small 2-stroke engines, running 5–6 hr per day, but only very noisy 1–2 times per week. No temporary deafness or tinnitus noted.

Case B

Aged 16 years, 7 months.

Had only fired about 6 rounds 0·22 in. rifle at funfairs (right shoulder).

Industrial noise-exposure:

Surface worker at a coal-mine for 18 months. A clattering noise; not *very* noisy, but had to raise voice to be heard. No temporary deafness or tinnitus noted.

Case C

Aged 18 years.

Had never fired a gun of any type.

Industrial noise-exposure:

Copper-smith for 2 years, 8 months. Hammering and riveting; very noisy. No temporary deafness or tinnitus noted.

Note the clinical findings in these cases together with those of Fig. 2 were such that the losses could be considered with certainty as being perceptive.

In addition to the cases mentioned above, other industrial noises from which hearing losses (a high-frequency notch of 15 dB or more) had resulted in some of the 111 subjects were:

Blacksmith, coal face (machine cutting and blasting): 2 subjects each.

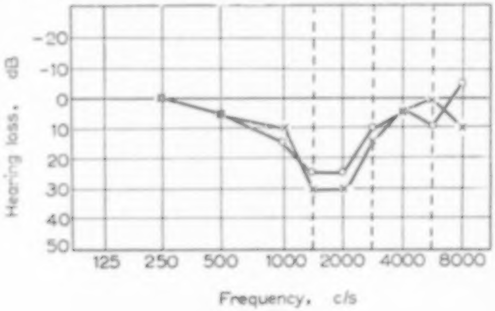
Aircraft riveting, plumbing (hammering), printing, riveting (by hand), timber mill, tube mill, welding (with hammering and banging): 1 subject each.

Thus at least 13 per cent of the men examined had a detectable hearing loss due to industrial noise-trauma.

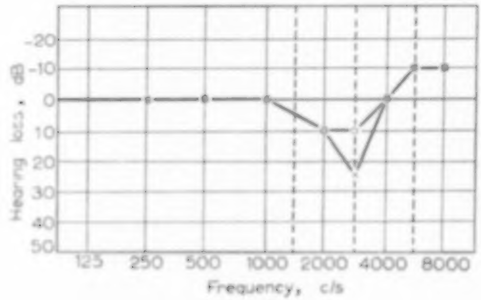
As part of the detailed consideration of the auditory acuity of this group of young men, reference has to be made also to the effects of small-arms fire, to which a high proportion have been exposed in school cadet forces and in sport. The resulting hearing defects are generally difficult to distinguish from those due to typical industrial noises and it is therefore pertinent to mention their occurrence in the proceedings of this Conference. Unless specific enquiry is directed during a hearing conservation programme towards such spare-time activities, it is more than a theoretical possibility for a high-frequency notch to be attributed to noisy working conditions whereas, in fact, it could be due to participation in shooting as a pastime.

It is noteworthy that only 36 per cent of the recruits examined had, on entry, never fired a gun larger than an air-rifle, and 50 per cent had fired 10 rounds or more of the larger fire-arms with an average of 454 rounds (falling to 253 if one man claiming over 10,000 rounds is omitted). Particularly little attention is paid to the possibility of damage to hearing being caused by the popular 0·22 in. rifle with its somewhat puny note compared with the sharp crack of the 0·303 in. counterpart. Many 0·22 in. rifles are fired on reverberant indoor ranges and no one concerned

appears to consider any form of ear protection to be necessary. In this material it has been found that a number of audiogram dips in the region of 1500 to 2000 c/s



Case D



Case E

FIG. 2. Audiograms of 2 cases of acoustic trauma due to gunfire.
Air conduction: right ○—○—○
left ×—×—×
Instrument make: Amplivox, Model 61, Serial No. 298.
Corrected to British Standard normal thresholds.
Recorder: J. J. K., February 1958.

are linked with innocuous noise-histories, except for admission of occasional practice with this rifle. Case D, in Fig. 2, is one example, and Case E shows the effect of arms of larger calibre. The details of these two men are as follows:

Case D

Aged 19 years, 1 month.

Had fired about 500 rounds of 0·22 in. rifle as member of a rifle-club in the previous 3 years. Last occasion—6 months before test. Never noticed any temporary deafness or tinnitus. Fired from right shoulder.

Industrial noise-exposure:

None. Had worked in a quiet section of British Railways, and as a nursing auxiliary for 8 months.

Audiometric bone-conduction tests confirmed loss as perceptive in type.

Case E

Aged 18 years, 4 months.

Claimed to have fired, in the last 5 years, some 1500 rounds of 0·303 in. rifle,

50 of 0·410 in., 200 of 12-bore shot-guns, and some 10,000 rounds of Bren, Sten, Lewis and Vickers guns in the Army Cadet Force. (From the right shoulder, when relevant.) No temporary deafness or tinnitus noted.

Industrial noise-exposure:

None. Worked as a photographer and with a newsagent.

Apart from the 0·22 in. rifle, there appears to be no other marked association between a particular weapon and the frequency at which the initial hearing loss is maximal. In general it may be stated that most weapons, in common with most industrial noises, cause an initial hearing loss at 4000 c/s, but in a few individuals the notch may appear first at 3000 or 6000 c/s. Each of the effects mentioned can be seen in cases shown in the figures.

DISCUSSION AND CONCLUSIONS

The survey has revealed the amount of damage to hearing which an unexceptional sample of young men has suffered from industrial noise-trauma within about 3 years after leaving school. All the men had been sufficiently long removed from any noise hazard for temporary hearing losses to have recovered. Sufficient justification of the normality of the control group (in spite of a small experience of gunfire noise) was considered to be obtained with the good agreement between the group thresholds and those of the 15 per cent having a negative history of past noise hazards and ear pathology. The extent of the median loss at 4000 c/s with respect to the control group of those at greatest risk (10 per cent) was not large (6·4 dB), but it must be borne in mind that the peak losses in these early cases were distributed over a frequency range of approximately 3000–6000 c/s and also that, by definition, half of the group had losses exceeding this figure.

A subsidiary, but not inconsiderable, cause of permanent hearing defects in the sample has been shown to be gunfire. The fact that 50 per cent of the recruits had, on entry, fired an average of more than 250 rounds, serves as a reminder of the severe hazard to those noise-susceptible men who are exposed to intense industrial noise during working hours and who fire small-arms as a sport.

None of the control group had noticed any difficulty in hearing or in understanding speech and all, of course, had passed the usual 20 ft whisper test. Other authors in this series have mentioned, however, that the auditory effects of industrial noise are cumulative and it follows that the more susceptible individuals are destined to become prematurely deaf if they continue working for many years in very noisy situations.

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THE SCOTTISH AUDIOMETER CALIBRATION SERVICE

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INTRODUCTION

THE purpose of this paper is to describe the organization and activities of the Scottish Audiometer Calibration Service, recently established by the Department of Health for Scotland and the Western Regional Hospital Board.

The need for accurate standards of auditory threshold has long been recognized. Measurements up to 1933 were correlated by SIVIAN and WHITE (1933). They defined threshold levels in terms of acoustic pressure at frequencies between 80 and 15,000 c/s at a point close to the ear drum. Another set of standards, based on tests with 342 normal subjects, was published by the United States Public Health Service in 1938. A third American investigation was made in 1939 on 3287 ears of visitors to the World's Fair in New York and San Francisco. These three surveys gave widely differing results. The data obtained by the U.S. Public Health Service have since been incorporated in an American Standard Specification for Audiometers for General Diagnostic Purposes, Z.24.5, 1951. In 1948 LUESCHER and ZWISLOCKI reported that the threshold levels delivered by audiometers adjusted in accordance with the U.S. Public Health Service standard were 10–15 dB higher than those demonstrated by tests on normal subjects among their own patients. Other otologists have made similar findings.

In Britain the preparation of audiometric standards which would conform more closely to the realities of clinical practice was begun in 1939 and completed in 1954 with the publication of British Standard Specification 2497: *The Normal Threshold of Hearing for Pure Tones by Earphone Listening.* The threshold levels defined in B.S.2497 are not much different (except at the two ends of the frequency scale) from those proposed in 1933 by SIVIAN and WHITE, but they are 10-20 dB lower than the current American standard.

The new specification of auditory threshold was widely applauded but little has yet been done to bring it into general use. The number of audiometers in Britain is not known but there are probably 400–500 in the hospital service and at least as many in other places, including the school medical service. The regular calibration of 1000 audiometers cannot be attempted without considerable technical and administrative facilities which are not yet available.

A small beginning has now been made in Scotland. An acoustics laboratory has been established at the Regional Physics Department of the Western Regional Hospital Board in Glasgow. Members of the department provide scientific, technical and administrative services for the new laboratory. A list of the equipment provided for the laboratory is given in Appendix 1.

ESTABLISHMENT OF STANDARDS

Acoustical standards are always difficult to establish or to reproduce, and those required in the calibration of audiometers are among the most elusive. The British

standard of auditory threshold is based on a particular type of earphone (S.T.C. 4026A) and of artificial ear (B.S.2042: *An Artificial Ear for Calibration of Earphones of the External Type*). For any earphone of type 4026A the excitation voltages corresponding to threshold loudness at various frequencies can be determined by reference to the standard earphone and artificial ear kept at the N.P.L. This information was obtained for two 4026A earphones obtained as subsidiary standards for the Scottish Audiometer Calibration Service. If all audiometers were equipped with earphones of this type, the calibration procedure would be relatively simple. In fact, four kinds of earphone (S.T.C., Telephonics, Permoflux and S. G. Brown, type K) are used in British audiometers of recent manufacture. For each of the three non-standard types the excitation voltages to give threshold loudness must be found by loudness balance tests.

These tests were carried out during July and August 1957 by a team of five observers using the following procedure:

(1) A 4026A earphone, excited to give a sound approximately 60 dB above the normal threshold, was applied to one ear.

(2) The earphone under test was applied with equal pressure to the opposite ear and supplied with a variable voltage input, under the control of the observer. A change-over switch enabled either (but not both) of the earphones to be energized. When the two sounds were judged to be of equal loudness, the excitation voltages were read from a valve voltmeter by a second observer and their difference was calculated.

(3) With the earphones in the same position, the electrical channel (oscillator, amplifier and attenuator) first used to supply the left earphone was switched to the right earphone and vice versa. The loudness balance was then repeated.

(4) The earphone first applied to the left ear was transferred to the right ear and vice versa. Tests (2) and (3) were repeated. The mean difference in excitation levels was calculated from the four sets of observations.

(5) The procedure just described was carried out at each of the ten test frequencies between 125 and 8000 c/s. Each observer performed tests (1) to (5) on ten occasions, making forty loudness balance judgments at each of the ten frequencies.

(6) The same cycle of measurements was made for a sample earphone of each type used in commercial audiometers.

(7) Each earphone (including the two 4026A sub-standards) was applied to the artificial ear and supplied with a suitable excitation voltage to give a sound 60 dB above the threshold of normal hearing. The output of the artificial ear was noted for each frequency. These observations formed the basis for performance tests on the audiometers submitted for calibration.

Results of the loudness balance tests on a Telephonics earphone were as given in Table 1.

The outcome of the loudness balance tests for this and the other two non-standard earphone types is summarized in Table 2.

Table 1. Difference in excitation levels, A-B, *in* dB, with standard deviations
A=S.T.C. 4026A, No. 1979 B=Telephonics

Frequency (c/s)	Observer A	Observer B	Observer C	Observer D	Observer E	Mean value
125	−4·2±2·8	−2·4±3·2	−2·8±3·5	−2·6±3·1	+0·3±3·0	−2·4±3·4
250	−3·2±2·8	−2·8±1·5	−2·8±2·6	−0·9±1·7	+1·2±1·6	−1·7±2·6
500	−2·1±2·4	−1·9±1·5	−2·9±1·7	−0·4±1·6	+0·3±1·9	−1·4±2·4
1000	0·2±1·3	+0·7±0·9	+0·1±1·3	+0·4±1·8	0±1·4	+0·2±1·4
1500	−1·1±2·7	+0·4±1·3	+0·6±1·9	+0·5±1·8	+0·8±1·7	+0·2±2·0
2000	−2·1±2·2	−1·2±1·6	+1·8±2·0	−0·1±2·1	+0·1±2·2	−1·0±2·1
3000	−3·4±2·4	−1·5±1·8	−4·9±1·5	−0·7±1·2	−2·2±1·7	−2·5±2·3
4000	−0·2±3·0	+1·4±1·7	+0·4±1·5	+3·4±2·2	+0·9±3·1	+1·2±2·6
6000	−1·3±2·1	+0·4±1·6	−2·5±2·2	+1·8±2·5	−1·4±2·6	−0·6±2·5
8000	−4·5±1·6	−2·7±1·8	−8·7±3·8	−3·2±3·2	−6·1±6·1	−5·0±3·5

Table 2. Difference in excitation levels, A-B, in dB, with standard deviations
A=S.T.C. 4026A, No. 1979

Frequency (c/s)	Telephonics	Permoflux	Brown
125	−2·4±3·4	−9·7±2·7	−22·3±4·4
250	−1·7±2·6	−6·0±2·2	−17·6±3·5
500	−1·4±2·4	−1·9±2·2	−18·6±2·8
1000	−0·2±1·4	+0·1±2·4	−11·2±1·6
1500	+0·2±2·0	−0·1±2·0	−6·6 ±1·9
2000	−1·0±2·1	−2·9±2·5	−4·3 ±1·8
3000	−2·5±2·3	−0·6±1·7	−8·1 ±1·9
4000	+1·2±2·6	−1·1±1·9	−10·7±2·2
6000	−0·6±2·5	−1·8±2·3	−19·7±3·6
8000	−5·0±3·5	−7·7±2·2	−23·3±3·2

Agreement among the five observers was reasonably good, though a bigger team would have been preferable.

INAUGURATION OF CALIBRATION SERVICE

By the end of August 1957, the appropriate reference levels had been established for all four types of earphones and the work of calibration could proceed. A census made by the Department of Health for Scotland, and modified slightly by later information, showed the presence of forty-nine audiometers in Scottish hospitals and associated clinics (Appendix 2). Two further instruments at the City General Hospital, Carlisle, were included for administrative convenience; they are under the charge of the consultants who have responsibility also for the Dumfries area. One hospital authority was hesitant about submitting its audiometer for calibration, but the other fifty have come forward. A few audiometers in the school medical service have also been examined, at the urgent request of the local authorities concerned.

ARRANGEMENTS FOR CALIBRATION

Each audiometer is brought to the Regional Physics Department or sent by passenger train at a time and date arranged beforehand. The calibration is performed and any necessary repairs are carried out within 24 hr; a few instruments needing extensive overhaul have been kept for a longer period. With the excellent help of British Railways a simple and reliable system has been evolved for transport from Edinburgh and more distant parts of the country. The audiometer is brought to the station at a specified time and placed in the guard's van of a through train to Glasgow. No wrapping or packing is necessary. A member of the Regional Physics Department meets the train on arrival and removes the audiometer. Similar arrangements apply for the return journey. Nearly thirty audiometers from various places in Scotland have so far made the double journey without damage or delay. No charge is made for the calibration and repair service, the running costs being borne by the Western Regional Hospital Board. Several members of the staff of the Regional Physics Department are involved in the calibration service.

The following tests and adjustments are made on each audiometer:

(1) Measurement, with artificial ear, of output levels at indicated hearing loss of +60 dB for each earphone and each frequency.

(2) Measurement of each output frequency.

(3) Measurement of all attenuator steps between 0 and +60 dB at 125, 250 and 8000 c/s.

(4) Continuity of cords, plugs and sockets.

(5) Cleaning of switches and contacts where necessary.

FINDINGS ON EXAMINATION OF 50 AUDIOMETERS

The results of tests on the first fifty audiometers were as follows:

1. *Output levels*

The output levels were measured at each frequency at 60 dB above threshold and compared with the values found by the standardizing procedure described in a previous section of this report. A complete table of the errors is contained in Appendix 3. Its contents may be summarized as follows:

Total number of output level measurements ...	874
Distribution of errors:	
Less than −20 dB	4
−20 to −15·1	7
−15 to −10·1	9
−10 to − 5·1	33
− 5·1 to − 0·1	84
0 to + 4·9	173
+ 5 to + 9·9	326
+10 to +14·9	217
+15 to +19·9	18
More than +19·9	3

It may be seen from Appendix 3 that not one audiometer out of the present sample of 50 instruments gives output levels within 3 dB of the standard values at

all frequencies. Six instruments (19, 34, 37, 46, 48, 50) are moderately satisfactory; the last three of these are from the same manufacturer. The other 44 audiometers are not up to the standard which their users might reasonably expect. Many of these instruments were found to be in poor condition mechanically and electrically. Their performance when new could not be inferred with much accuracy, but the output levels of a small number of completely new instruments were not much different from the general experience. The pattern of errors suggests an original calibration nearer to one of the American standards than to B.S.2497.

2. *Attenuator steps*

The 5 dB attenuator steps were checked in the range between 0 and +60 dB indicated hearing loss at 125 c/s and at 8000 c/s. The steps were generally within the limits 4–6 dB and it seems clear that a competent manufacturer does not need a tolerance any wider than this.

Total number of 5 dB attenuator steps measured:	
at 125 c/s	518
at 8000 c/s	387
Number of steps less than 4 dB or more than 6 dB:	
at 125 c/s	20
at 8000 c/s	12

3. *Output frequencies*

Total number of frequency measurements ...	463
Distribution of errors:	
0 to 1 per cent	203
1·1 to 2	117
2·1 to 3	51
3·1 to 4	21
4·1 to 5	7
More than 5	64

Output frequencies were generally within 3 per cent of the nominal values but in a number of instruments, including several from the same manufacturer, very large errors were found.

CORRECTION OF ERRORS

The substantial and abundant errors disclosed by the foregoing tests are the more regrettable because, in most of the audiometers examined, they cannot be corrected without radical alterations to the instrument. Only one British manufacturer provides adequate facilities for the adjustment of output levels and frequencies. In audiometers of this make the output levels have been brought to within 2 dB of the standard values and the frequency errors reduced to less than 1 per cent before the return of the instruments to their owners. Such adjustments are not possible with the other makes of audiometer that have been examined. It is therefore necessary to issue a calibration certificate showing the corrections applicable to the indicated values of hearing loss. Some audiometers have no trimmer condensers for the adjustment of individual frequencies and it has not been possible to eradicate the errors found during the calibration process. Thirty-six of the fifty audiometers

were found to be in need of repair in the department's workshops before the calibration could be done.

FUTURE ACTIVITIES

(1) So far it has been possible to measure output levels for air conduction only. Standards for testing bone-conduction receivers are in preparation. In particular, agreement is expected shortly on the design of an artificial mastoid as the outcome of a long programme of work at the N.P.L. Regular calibration of bone-conduction receivers will be provided as soon as the necessary instruments can be obtained.

(2) A large number of audiometers used in the school medical service should certainly be included in the calibration scheme. Certain administrative difficulties, including the provision of an additional Scientific Assistant, remain to be overcome before the service can be extended in this way. The evidence so far available suggests that the accuracy of audiometric measurements is no better in school clinics than it was in hospitals a few months ago.

(3) It is intended that each audiometer shall be sent for calibration two or three times each year. The interval between successive examinations will be determined in the light of experience gained during the first year or two of the service.

Acknowledgements—The work described in this report has been made possible by the assistance of many organizations and individuals. Members and officials of the Western Regional Hospital Board and the Department of Health for Scotland have contrived the administrative framework and material resources of the new service in a characteristically helpful way. Several manufacturers have co-operated generously. Members of the Physics Division of the N.P.L. have given freely of their abundant knowledge and technical experience. Scottish otologists have taken a lively interest in the service and have cheerfully endured the confusion resulting from the abrupt change in audiometric standards. To all of these friends and advisers grateful acknowledgment is now made.

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APPENDIX 1

EQUIPMENT USED IN AUDIOMETER CALIBRATIONS

Bruel and Kjaer Laboratories Ltd.:

Artificial ear, type 4109
Frequency analyser, type 2105
Frequency response recorder, type 3302
Wide-range voltmeter, type 2405
Microphone amplifier, type 2601
Condenser microphone, type 4111
Microphone cartridge, type MK.0002
Artificial voice, type 4210

Standard Telephones and Cables Ltd.:

2 Calibrated receivers, type 4026A
2 Probe tube microphones, type LU.3284A

Amplivox Limited:
Audiometer, model 61

Muirhead and Co. Limited:
Valve-maintained tuning-fork, type D-630-B

Newalls Insulation Co. Ltd.:
400 acoustic tiles, 18 in. × 18 in. × 1 in.

The total cost of this equipment was about £2000.

APPENDIX 2

HOSPITALS AND CLINICS USING THE SCOTTISH AUDIOMETER CALIBRATION SERVICE IN 1957

	Number of audiometers
Northern Region	
Royal Northern Infirmary, Inverness	2
North-eastern Region	
Aberdeen Royal Infirmary	4
Royal Aberdeen Hospital for Sick Children	1
Eastern Region	
Dundee Royal Infirmary	3
Stracathro Hospital	1
South-eastern Region	
Royal Infirmary, Edinburgh	4
Eastern General Hospital, Leith	1
Deaconess Hospital, Edinburgh	1
Royal Hospital for Sick Children, Edinburgh	1
Leith Hospital	1
Peel Hospital, Galashiels	1
East Fortune Hospital	1
Western Region	
Western Infirmary, Glasgow	2
Killearn Hospital	1
Ear, Nose and Throat Hospital, Glasgow	1
Hearing Aid Clinic, Woodside Crescent	4
Glasgow Royal Infirmary	4
Victoria Infirmary, Glasgow	2
Stobhill General Hospital	1
Springbank Clinic, Stirling	3
Falkirk and District Royal Infirmary	1
Ayrshire Hospitals	6
Kilmarnock Infirmary	1
Dumbarton Hearing Aid Clinic	1
Dumfries and Galloway Royal Infirmary	1
City General Hospital, Carlisle	2

APPENDIX 3

Errors in output levels of 50 audiometers

Correction factors, in dB, necessary to obtain true hearing loss from values indicated by audiometer

Serial No.	125	250	500	1000	1500	2000	3000	4000	6000	8000 c/s
1	+8 +7	+10 +9	+10 +9	+6 +5	+7 +6	+10 +9	+11 +11	+13 +12	+6 +2	+10 +8
2	+15 +12	+17 +16	+7 +7	+5 +5	+6 +6	+9 +8	+12 +12	+12 +12	+10 +10	+16 +15
3	+8 +9	+10 +10	+12 +10	+8 +5	+7 +6	+8 +8	+11 +11	+13 +14	+3 +3	+8 +9
4	+6	+9	+12	+9		+11		+16	+4	+6
5	+8 +8	+10 +10	+9 +9	+5 +6	+6 +7	+9 +9	+12 +12	+12 +12	+3 +4	+11 +14
6	+11 +11	+10 +12	+12 +12	+10 +10	+6 +6	+10 +10	+9 +10	+11 +12	+6 +5	+12 +12
7	+10 +9	+10 +10	+11 +10	+6 +6	+5 +4	+1 0	+3 +3	+8 +7	−3 −2	+3 +3
8	+10 +9	+9 +9	+11 +10	+6 +5	+5 +6	+15 +16	+13 +13	+7 +6	−10 −13	+15 +13
9	+8 +8	+11 +11	+11 +11	+6 +7	+6 +6	+11 +9	+13 +11	+14 +14	+5 +4	+12 +10
10	+6 +6	+10 +9	+8 +8	+4 +2	+3 0	−9 −7	+6 −7	+12 0	+20 +10	+6 −4
11	+9 +10	+11 +12	+11 +13	+10 +12	+7 +9	+9 +11	+9 +12	+10 +12	+4 +6	+11 +11
12	+8 +8	+11 +10	+12 +11	+7 +6	+7 +6	+13 +12	+12 +12	+10 +14	+10 +5	+19 +14
13	+7 +9	+9 +10	+10 +11	+6 +7	+4 +5	+7 +7	+5 +6	+10 +11	−2 −2	−7 −17
14	+9 +9	+10 +11	+11 +12	+6 +7	+5 +6	+8 +9	+10 +10	+10 +11	+5 +3	+11 −2
15	+9 +9	+11 +11	+11 +11	+9 +8	+6 +5	+9 +9	+11 +11	+14 +13	+4 +4	+7 +9
16	+7 +8	+7 +9	+7 +10	+3 +7	+4 +7	+5 +6	+8 +7	+8 +9	0 0	+10 +8
17	+9 +8	+12 +12	+13 +11	+10 +7	+5 +4	+8 +8	+10 +10	+12 +12	+3 +2	+10 +11
18	+6 +6	+8 +8	+9 +9	+5 +6	+4 +5	+7 +8	+9 +9	+11 +13	+3 +3	+8 +8
19	+6 +5	+7 +6	+8 +7	+5 +3	+3 +2	+3 +2	+2 0	+5 +4	−6 −7	+4 +4
20	+8 +9	+11 +10	+10 +10	+7 +7	+5 +5	+9 +10	+13 +12	+13 +11	+8 +6	+12 +10

Serial No.	125	250	500	1000	1500	2000	3000	4000	6000	8000 c/s
21	+10 +11	+12 +12	+12 +12	+8 +8	+8 +8	+11 +11	+13 +12	+16 +15	+6 +5	+9 +9
22	+9 +9	+10 +10	+10 +10	+6 +6	+7 +6	+9 +9	+11 +10	+12 +12	+4 +4	+11 +11
23	+9 +9	+11 +11	+12 +11	+6 +6	+6 +6	+8 +9	+9 +10	+12 +12	+1 +2	+8 +9
24	+9 +8	+10 +8	+12 +9	+7 +5	+4 +2	+6 +6	+3 +4	+7 +10	−5 −7	+7 +4
25	−8 +7	−2 +10	+1 +10	−2 +6	+1 +6	−5 +10	+10 +12	+7 +14	+2 +4	+7 +2
26	+7 +8	+10 +10	+11 +12	+8 +9	+7 +7	+12 +12	+12 +12	+13 +13	+7 +4	+10 +11
27	+8 +7	+12 +12	+13 +12	−5 −3		+10 +11		+14 +15	+4 0	+14 +12
28	+6 +5	+9 +10	+9 +10	+7 +6	+6 +6	+10 +10	+11 +10	+14 +16	+3 +5	+10 +11
29	−40 −40	+10 +10	+10 +10	+10 +10	+5 +5	+10 +10	+10 +10	+15 +15	+5 +5	+5 +5
30	+10 +7	+11 +8	+10 +7	+10 +7	+10 +6	+12 +9	+11 +9	+13 +10	+6 +3	+12 +11
31	−13 +11	+14 +13	+13 +12	+11 +10	+8 +7	+11 +10	+11 +12	+13 +12	+4 +5	+13 +10
32	−12	−6	0	+3		+4	−4	−2	−11	+3
33	+5	+10	+10	+5		+10	+1	+11	−6	+6
34	+6	+6	+5	+4		+3	0	+5	−1	+4
35	−5	−4	0	+1		+15	−4	−2	−10	+3
36		+2	+2	+1		+1	+6	+8	0	+2
37	−3 +2·5	+3 +3	+7 +6	+2 +2		−2 −1	+1 +3	+4 +7	+1·5 +6	−7 −4
38	−16	−18	−5	+6		−6		+16		−3
39	−8	0	+21	+18		+19		+1		−9
40	−13 −14	+2 +2	+10 +11	+6 +8		−4 −3		+5 +7		+6 −5
41		0	+7	+6		+3		+4		+32
42	+6 +3	−1 −4	+1 −1	0 −2	−4 −10	+4 +2	−2 +2	−2 −1	+9 +12	+14 +16

Serial No.	125	250	500	1000	1500	2000	3000	4000	6000	8000 c/s
43	−4	−8	−5	−5	−16	−8	−12	−20	+4	−1
44	+1 −1	−6 −10	+1 −4	+1 −6	−5 −13	+2 −4	−2 −3	−8 −16	+9 +4	+10 +3
45	+4 +7	−2 +1	+5 +5	+1 +1	−3 −5	+2 +1	+6 +5	−3 −7	+11 +11	+11 +15
46	+5 +5	+4 +3	+2 +2	+4 +3	+5 +4	+3 +3	−1 0	+6 +6	0 −1	−2 −2
47	−8 −29	−7 −24	−7 −7	−10 −6		−3 −2		−13 −8		0 −1
48	+3 +3	+3 +3	+1 +1	0 +2	0 −1	+2 +1	−2 −1	+3 +3	+2 0	−15 −1
49	+2 +2	+5 +5	−3 −4	0 −1	−4 −3	−4 −4	+5 +3	−1 −1	+11 +9	+13 +10
50	+7 +6	+2 +3	−1 0	+2 0	+2 +2	−1 0	0 −2	+2 +2	−1 −1	−3 −3

Figures in the two rows opposite each serial number refer to the two earphones used with the audiometer

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METHODOLOGY OF AIR-CONDUCTION AUDIOMETRY FOR HEARING SURVEY

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1. INTRODUCTION

THE recent rise in noise consciousness in industry in particular, and in people in general, has served as a stimulus to both more intensive and more extensive noise control. Owing to variations in individual susceptibility to noise (URBANTSCHITSCH, 1895; LARSEN, 1953), it is impossible to predict satisfactorily the noise-induced hearing loss in a given individual. Only by actual measurements of individual hearing loss can a satisfactory answer be obtained. Thus, an adequate programme of noise control directed towards hearing conservation must be based on serial audiometry with pre- and per-employment hearing tests. It is merely a matter of time before hearing surveys become a regular feature of industrial medicine. Furthermore, in an effort to obtain comparative data and, at the same time, obtain information on the prevalence of deafness in general, community surveys will be essential. So far, there has been little uniformity of standards or of procedure in the conduct of the few hearing surveys that are being, or have been, done in this country. It is the purpose of this paper to present our method of approach, developed on our experiences in this field. We also hope that the contents will find wider application, and be of some help to those embarking on audiometric work.

It is convenient to approach the problems in threshold audiometry by considering the various factors concerned in the whole procedure, with a discussion of their relative importance and the variabilities occurring in them. These various factors are classified and tabulated in Table 1.

TABLE 1. FACTORS DETERMINING THE RECORDED THRESHOLD OF HEARING

I. *Physical Factors*

A. *Audiometer* (*viz. electrical*) *Signal at Output*

This is determined by:

(i) The initial instrument settings and characteristics.

Errors in calibration (consider together with earphones, see below), i.e. errors in zero hearing loss, in frequency and in nominal values of attenuator steps. Impurity of wave form.

(ii) Acquired errors and fluctuations re:

(*a*) Intensity

1. Misalignments of the attenuator dial.
2. Thermionic valve failures.
3. Development of open circuits on resistor chains.

TABLE 1. (*contd.*)

4. Resistors or condensers breaking down or changing value due to overheating.
5. Electrical leaks.
6. Variations in electrical input.

(*b*) Frequency

Oscillator drift.

1. Oscillator drift.

(*c*) Introduction of noise

1. Noisy contact of attenuators.
2. Valve failures, especially output valve.
3. Loose contacts.

B. *Integrity of Leads*

Errors may occur due to:

1. Oxidation of lead connexions.
2. Use of incorrect jacks.

C. *Earphone Characteristics*

Consider together with audiometer and leads in calibration of instrument as a whole.

Errors may occur re:

(*a*) Intensity

1. Ageing processes—associated with (*b*) 1.
2. Damage due to dropping.
3. Complete breakdown of earphones due to fatigue.
4. Variation in sensitivity due to temperature variations.

(*b*) Frequency response

1. Earphone diaphragm fatigue—especially plastic diaphragms.

D. *Earphone Cushion and its fit on Skull*

1. Type of cushion.
2. Pressure of cushion on skull (related to D.3).
3. Presence/absence of air leaks (related to D.2).

E. *Ambient Noise*

Apart from noise in the audiometer channel, additional noise that may mask the test tone may arise from extraneous conditions.

F. *Miscellaneous Factors*

Size of attenuator steps.

II. *Psycho-physical Factors*

1. The normal threshold of hearing.
2. Criterion of threshold: procedure.
3. Reliability of audiometry.

III. *Psychological Factors*

1. Attitude of the observer.
2. "Learning."

Table 1 (*contd.*)

IV. *Pathological Factors*
A. *Temporary*
(i) Noise-induced hearing loss: auditory fatigue and adaptation (in part "Physiological").
(ii) Other factors: "colds"; cerumen; acute otitis media.
B. *Permanent*
(i) The ageing process: trend or presbycusis curves.
(ii) Deafness and hearing defects other than presbycusis:
(*a*) Conductive deafness
(*b*) Perceptive deafness:
1. Other than noise-induced.
2. Noise-induced:
Occupational hearing loss.
Acoustic trauma.

C. *Cross-hearing in Deaf Cases*

2. PHYSICAL FACTORS

For convenience, we shall discuss these factors under seven headings:

(*a*) Characteristics of the audiometer
(*b*) Acquired defects in the instrument
(*c*) Ambient noise
(*d*) The earphones and the cushion—pressure of application on the ear
(*e*) Size of attenuator steps
(*f*) Control of physical factors: calibration and monitoring
(*g*) Correction of errors in physical factors.

(*a*) *Characteristics of the audiometer*

In a recent study, Lenihan (1957) and his team were able to investigate 98 per cent of the audiometers in Scottish hospitals. They found that not a single audiometer out of that sample (a total of 50 instruments) gave output levels within 3 dB of the British standard (B.S.2497) values at all frequencies. When the total number of output level measurements was considered, it was found that the error was ± 20 dB or more in some cases, and ± 10 dB or more in nearly 30 per cent of cases, whilst the error was less than ± 5 dB in less than 30 per cent of cases. The pattern of errors suggested an original calibration nearer to the American standard of the normal threshold of hearing.

Lenihan remarked that many of the instruments were found to be in poor condition, mechanically and electrically, and their performance when new could not be inferred with much accuracy, but the output levels of a number of completely new instruments was little different.

Frequency errors do not occur as often, and are not as serious, as intensity errors. However, Lenihan found that, out of a total number of frequency measurements, nearly 20 per cent had an error of more than ± 3 per cent, which is the tolerance permitted by the *British Standard for Pure Tone Audiometers* (1958), which

has just been issued by the British Standards Institution. Moreover, in the *Medical Research Council Special Report on Hearing Aids and Audiometers* (1947), one of a sample of five audiometers had a frequency error of $+11$ per cent at one frequency and $+6{\cdot}5$ per cent at two other frequencies. The report points out that reduction in frequency error is necessary for the following reason. Most audiometer receivers have a fairly steep fall in sensitivity between about 4 kc/s and 8 kc/s. Thus in the region of 4 kc/s, the locus for acoustic trauma, a frequency variation of ± 5 per cent would in some cases correspond to a variation in output of as much as 6 dB.

LENIHAN (1957) found that the attenuator step values were outside the limits 4–6 dB in only 3–4 per cent of cases. This tolerance is given in the *British Standard for Pure Tone Audiometers*.

As the M.R.C. Special Report mentioned above remarks, purity of the wave form is important since the presence of harmonics or other extraneous tones may either mislead a subject into making a wrong judgment of the threshold level, or, by masking, may actually modify the subject's threshold level. The presence of harmonics is more disturbing at the lower frequencies, but their complete eradication is not practicable. The *British Standard for Pure Tone Audiometers* states that the level of any harmonic should be at least 30 dB below the level of the fundamental. The *Medical Research Council Special Report* said that one of three sample audiometers tested showed a second harmonic only 20 dB below the fundamental test tone frequency 128 c/s.

(*b*) *Fluctuations in output and acquired defects*

Even the best audiometers that are commercially available may develop faults, despite their initial conformity to either the American or British Standards.

As WATSON and TOLAN (1949) remark, the audiometer receiver is almost always responsible for variations in the overall output or calibration. They give the results of an 1800-hr-life test on one accepted audiometer. These results show that the electrical output of the audiometer hardly changed by one decibel, but in the acoustical output there were peculiar changes, which were more marked at the low and high frequencies. At 8 kc/s, the acoustical output fluctuated over a range of 14 dB. Manufacturers now claim that this phenomenon is largely prevented by a pre-ageing process. This ageing process is a function of the diaphragm material, and is not so marked with metal as it is with plastic diaphragms. Earphones with metal diaphragms, e.g. the S.T. and C. type 4026, are therefore preferable.

Dropping or rough handling the receiver may cause it to weaken 5 to 10 dB or more at certain frequencies. Such damage is rarely to the same degree at all frequencies (WATSON and TOLAN, 1949).

In general, however, in an audiometer with pre-aged receiver, fluctuations of less than $0{\cdot}5$ dB occur in the audiometer output at the receiver. This is most probably due to fluctuations in the mains electricity supply and to temperature variations affecting the earphones. In field work, it will be found that electrical mains supply fluctuations are not uncommon. Although most audiometers are designed so that fluctuations in the mains supply voltage does not appreciably affect their performance characteristics, we consider it a wise precaution to guard against this as a source of error by having a voltage stabilizer available for use should monitoring

show appreciable fluctuation of the mains voltage. The output of some mains-operated instruments increases 2 to 4 dB when the mains voltage increases from 200 to 250 V (*Medical Research Council Special Report* No. 261, 1947). Telephone receivers may increase in sensitivity by 1 dB for each 10° F rise in temperature. The temperature coefficient for receivers with plastic diaphragms is much less.

Faulty "hearing loss" readings may occur due to misalignment of the attenuator dial. Frequently this is produced by the operator swinging the dial vigorously against the end stop. An error of 5 or 10 dB may result. The development of open circuits on the resistor chain may produce errors of the order 10–20 dB.

The most frequent cause of a fall in the receiver output by more than about 20 dB is a faulty valve, especially the output valve. Less frequently, faults are traceable to resistors or condensers breaking down or changing value due to overheating.

In general, audiometer faults that produce appreciable change in the output are irreversible. However, we have known an intermittent fault to develop in the audiometer used on one particular survey, and this fault eluded the subjective monitoring for several days before it was confirmed. It is therefore unwarranted to assume, as is so frequently done, that any appreciable change in the performance characteristics of an audiometer is irreversible. When the initial proposals for audiometer standards were being drawn up by the Electro-Acoustics Committee of the Medical Research Council, it was suggested that these instruments should incorporate a voltmeter or similar monitoring instrument. In our opinion, the failure of manufacturers to adopt this advice should be severely criticized.

On one occasion it was noted that an audiometer, reported as acceptable by physical standards, i.e. electrical output measurements and coupler calibrations, gave a bimodal distribution of the hearing losses when a number of subjects were tested. As other audiometric tests showed, this distribution was not a function of of the sample, but of the audiometer. There was probably some form of electrical leak. This fault cannot be detected by physical means, and must be excluded by testing a number of subjects with the selected audiometer.

A loss in one earphone but not in the other suggests a defect in that receiver or its lead. Generally, when a telephone becomes faulty it is due to complete breakdown and not to a change in sensitivity. Defects in one or other lead may give fluctuant errors of the order 15–20 dB. We have seen such an error that was attributable to use of the incorrect jacks. Oxidation of the lead connexions may also give rise to errors in the earphone output.

Acquired frequency errors may occur due to oscillator drift but are usually not appreciable.

Noisy contact of attenuators, which occurs after a long period of use, is a not infrequent cause of trouble in audiometers. Faulty valves may also give rise to a noisy acoustic output.

(*c*) *Ambient noise*

Ambient noise may mask the test tone and raise the threshold of hearing. This effect is more marked for the lower audio-frequencies since (*a*) ambient noise, in general, has a greater lower-frequency content, and (*b*) the acoustic insulation afforded by the earphones diminishes with decrease in frequency.

Minimum acceptable octave-band noise levels for audiometric rooms have been

drawn up (WEBSTER, 1954; COX, 1955; GLORIG and HARRIS, 1957). The curves indicate the sound pressure levels that will just mask given audiometer test tones. Screening tests for given equivalent hearing losses can be conducted in rooms if the noise levels do not exceed the correspondingly labelled parameters. A listener with normal hearing can just hear the test tone with the audiometer dial at zero when the ambient noise is not more than 40 dB for each of the low octave bands, 75–150 c/s, 150–300 c/s, 300–600 c/s and 600–1200 c/s.

To conform to the M.R.C. Electro-Acoustics Committee's recommendations (*Requirements and Technique of Usage of Pure Tone Audiometers*, 1952), the ambient noise level must be less than 40 dB, as measured on a sound-level meter conforming to the American Standards Specification.

A good solution for a sufficiently quiet test room is provided by a mobile sound-treated unit, which is mandatory if community surveys are contemplated. A two-room (one for the operator and the audiometer, the other for the subject) set-up is preferred.

The first mobile booth, constructed by the Royal Canadian Air Force Mobile Otological Laboratory, consists of a sound-proof chamber mounted on a truck. Sound exclusion is achieved by making the chamber of three concentric $\frac{3}{16}$ in. steel plate cylinders, the inner surfaces of which are lined by hair felt and isolated from one another by rubber shock mounts. This arrangement produces sound attenuation of the order of 55–60 dB, according to the frequency (SULLIVAN and HODGES, 1952).

The Royal Air Force and Royal Navy also have similar mobile units. The Royal Air Force Mobile Hearing Research Unit is mounted on a 7-ton Bedford general service chassis and contains two compartments, i.e. an ante-chamber and a triple-walled sound-proof cell, the test chamber, both of which are constructed of 1 in. oak planks covered with aluminium sheeting. The spaces between the walls and the ceilings of the test chamber are filled with hair felt, and the spaces between the floors with fibre-glass quilting. To achieve internal dampening, both chambers are lined with perforated "hardboard" backed by fibre-glass and the floors are covered with "Airtread" rubber flooring (DICKSON and WHEELER, 1953).

Recently, a three-roomed mobile unit has been built for the Medical Research Council at their Pneumoconiosis Research Unit in South Wales. This represents an advance on the Air Force unit, since there is more room for clinical examinations; running warm water for aural syringing is available, and there is a built-in X-ray unit. Particulars of the construction of this unit are given in Appendix 1 with Figs. 1 and 2.

If a mobile audiometric unit is not used, a special audiometric room may be built or an already existing room can be sound-treated. The two-section series 400-CT audiometric unit available from the Industrial Acoustics Co. of New York combines both the subject's room and the operator's room in one structure, whilst "MAICO" of Minneapolis can supply the pre-fabricated, demountable Burgess-Manning Sound Room. As the Guide for Conservation of Hearing in Industry issued by the American Academy of Ophthalmology and Otolaryngology points out, the best results in sound treatment of an existing room are obtained by consultation with an acoustic engineer. Should these services not be available, the Guide offers a method of sound-treating an existing room.

(d) The earphone cushions

GLORIG and HARRIS (1957) state that different cushions on the same earphone may change the acoustic output by 8 dB or more. The calibration procedure, however, takes this factor into account (see below).

The *British Standard for Pure Tone Audiometers* says that the force of application of the earphone to the human ear should be as close as possible to the value 500 g weight. It is doubtful whether this is an important factor responsible for significant threshold variations, but air leaks between the cushion and the ear may be responsible for errors of the order of 5 dB (rise in threshold), especially for the threshold at lower frequencies, and so it is important to ensure that an adequate ear seal is maintained throughout the testing procedure.

(e) Size of the attenuator steps

Clinical audiometers have 5 dB attenuator steps. The *British Standard Threshold of Hearing* is, however, based upon two studies each of which employed instruments with 2 dB steps. Elementary statistical considerations indicate that a threshold determined by an instrument operating in 2 dB steps will, on an average, be 1·5 dB lower than that obtained from an instrument moving in 5 dB steps.

(f) Calibration and monitoring

Calibration implies a determination of the characteristics of the audiometer, whilst monitoring is a check on the audiometer when in operation to ensure that there is no significant change in these characteristics. Therefore, in general, calibration implies a laboratory procedure, and monitoring a field procedure.

In conjunction with the *calibration*, it is convenient to examine the audiometric equipment for signs of wear and tear. The scheme adopted by the Scottish Audiometric Calibration Service (LENIHAN, 1957) may be recommended. The following tests and adjustments are made:

(1) Measurement of output levels at indicated hearing losses of +60 dB for each earphone and each frequency
(2) Measurement of each output frequency
(3) Measurement of all attenuator steps between 0 and +60 dB at 125 c/s and 8000 c/s
(4) Examination of the continuity of cords, plugs and sockets
(5) Cleaning of switches and contacts where necessary.

In addition, one should add that an audiometer used for research purposes should be studied for the purity of the wave form. The harmonic content of the sound output is measured by means of a wave analyser and an artificial ear.

As the *British Standard for Pure Tone Audiometers* remarks, the objective calibration of the earphone, including any detachable earcap if fitted, shall be carried out with an artificial ear* conforming with B.S.2042. In the case of earphones of the pattern maintained at the N.P.L. as a reference standard, this objective calibration, combined with the data given in B.S.2497, para. 3, Table 2, suffices to calibrate the earphone in terms of the standard normal equivalent threshold sound

* Couplers are referred to in U.S. terminology. These are cavities of predetermined form used for the loading of earphones, whereas artificial ears simulate the loading of an average ear.

pressure level. However, it is uncommon for earphones fitted to commercial audiometers to be the same pattern as the reference standard, i.e. the S.T. and C. 4026A. The earphones must therefore be compared subjectively with a calibrated earphone of the standard type by equal-loudness balancing at low or moderate loudness levels, and thereafter all earphones of the same type can be calibrated objectively on the artificial ear.

Calibration of the masking properties of the noise generator as a function of frequency is also necessary, since the figures assigned to the masking scale often bear no relationship to the masking properties of the noise. For this calibration, the masking noise and the audiometer signal are fed into the same earphone and the shift in a subject's threshold of hearing produced by a given output of the generator is measured.

After the physical calibration, twenty otologically normal subjects should have their hearing tested to ensure that the distribution of results is unimodal. This will ensure against an audiometer with the type of sporadic electrical leak that was previously described.

Monitoring an audiometer is customarily done by serial audiograms of a reference subject, who is readily available during the course of the hearing survey or investigation, or the operator. Such a procedure, admittedly a subjective one, is sufficient to detect changes in the audiometer's performance of 5 dB or more and, if performed daily, is an adequate safeguard against the usually encountered failures which may occur in the instrument. However, our experience shows that this monitoring procedure alone is inadequate, since intermittent faults may develop (see above).

The ideal monitoring in audiometry would be measurement of the sound stimulus delivered to the subject's ear at the time of the test. This suggests some form of probe microphone to measure the acoustical pressure in the external auditory meatus, but such a procedure is practicable only under experimental laboratory conditions. Moreover, it is impossible to measure the acoustical pressure of the sound stimulus at or near the threshold of hearing except by the use of a complicated selective equipment, and the results obtained by the probe microphone at a high intensity level must be extrapolated to estimate the probable values at or near the threshold levels of hearing.

The most convenient method for general use is monitoring of the electrical output of the audiometer up to the terminals of the telephone receivers. This presents no difficulty, even under field conditions, and can be achieved by a calibrated oscilloscope or a valve voltmeter. Here again, the output at or near the threshold of hearing cannot be measured, and both instruments introduce the additional complication that they themselves are electronic devices and liable to faults. It is possible, however, to have non-electronic monitoring of the audiometer output by the use of an a.c. rectifier voltmeter coupled to the audiometer by a transformer. Using this device, it is possible to measure the electrical output for intensities of the test tone corresponding to 50–80 dB hearing loss for air conduction, and 20 dB hearing loss by bone conduction. Because of this feature, it is possible to monitor an actual test tone, since the intensity is insufficiently loud either to disturb the subject or to produce temporary hearing loss.

Unfortunately, this method of audiometric monitoring gives no information either

regarding the leads distal to the checking point or regarding the earphones themselves. However, provided the correct jacks are used and the plug surfaces are kept free from oxidation and lightly lubricated, no faults should develop in the contacts. The faults which develop in earphones are usually irreversible and of such a magnitude that they command immediate attention. To assess the influence of temperature on the earphone calibration, we have installed a wall thermometer in the subject's booth.

We find that use of the rectifier meter together with daily full-frequency tests of a normally-hearing person and a subjective check by the operator before each audiogram is done affords a simple but adequate and comprehensive monitoring of the audiometer. The pre-audiometric subjective check is done by the operator on himself by putting the signal on-off switch in the "fixed" position and the intensity of the tone just above threshold. The test tone is then alternately fed into one earphone, then the other. Only a little experience is required to detect a change in the acoustic output of the earphones. For this test, two frequencies only need be used. We suggest 2 kc/s and 250 c/s. A test tone of the first frequency is easier to detect, whilst an apparent change in threshold for the second frequency, without corresponding changes in the first frequency, would indicate changes in the ambient noise. This is one feature of subjective monitoring techniques which is not covered by objective audiometric monitoring techniques. Another method of "ambient noise monitoring" is for the audiometrician to accustom himself to listening in the subject's booth at the beginning of each session to ascertain whether any particular noise is audible. If a sound-level meter is available, serial overall sound-level readings can be taken in a minimum of time.

(g) *Correction of errors*

As LENIHAN (1957) remarks, the calibration errors in most audiometers cannot be corrected without radical alterations to the instrument. Only one British manufacturer provides adequate facilities for the adjustment of output levels and frequencies. The construction of calibration correction curves is, at the most, only a second-best solution.

3. PSYCHO-PHYSICAL FACTORS

(a) *The normal threshold of hearing*

Zero hearing loss on the audiometer attenuator scale corresponds to the normal threshold of hearing. The *Glossary of Acoustical Terms* (1955) defines the normal threshold of hearing as the modal value of the thresholds of hearing of a large number of otologically-normal observers between 18 and 25 years of age. However, the modal acoustic pressures obtained by the studies (DADSON and KING, 1952; WHEELER and DICKSON, 1952) on which the *British Standard for the Theshold of Hearing* (B.S.2497) is based are appreciably lower than those (*National Health Survey, United States Public Health Service, Bulletin* 4, 1938) on which the *American Standard for the Threshold of Hearing* is based. Consequently, an audiometer calibrated to the American standard shows an acoustic output at zero hearing-loss reading which is 5 to 15 dB greater (depending on frequency) than an audiometer calibrated to the British standard. More recent studies in France (LEHMANN, 1956; CHAVASSE and LEHMANN, 1957) show a

threshold which, for frequency of 500 c/s and above, is even lower than the British standard.

Glorig *et al.* (1956) claim that the difference between the results of the American and British studies is due to the inherent difference in experimental technique between laboratory and survey type studies.

To specify a modal point as the normal threshold implies variation between normal individuals. The U.S. Public Health Survey found a standard deviation of the order of 6 dB, which Dadson and King (1952) also found to be the case in their study over the frequency range 1 to 3 kc/s. For frequencies of 6 kc/s and above the standard deviation was of the order of 9 dB or more.

(b) The criterion of threshold: procedure

Inasmuch as each and every audiometric test is a psycho-physical experiment, the indoctrination of, or "patter" given to, the subject is most important. We have used the following "patter":

> "Your hearing will now be tested by asking you to listen through these headphones to a number of simple musical tones. Each ear will be tested separately, beginning with the right/left [specify] one, and every time you hear a tone, no matter how loud or how quiet it may be, you are to press this button. Keep the button pressed as long as you hear the sound, and release it as soon as you think that the sound has disappeared." (Demonstrate by long and short signals.)

Since pure-tone audiometry is a practical application of that classical psychophysical procedure known as the method of limits, the threshold to be recorded will be that value which is midway between the descending threshold and the ascending threshold. The threshold is defined as that level which gives a 50 per cent response to the stimulus. We have adopted the following procedure:

(1) Present a tone lasting about 2 sec at an intensity which is expected to be about 40 dB above the subject's threshold at that frequency.

(2) If this is heard, present successive tones each 10 dB lower than the preceding one until the signal is no longer heard. This will give an *approximate threshold*.

(3) Return to the intensity to which the subject last responded and present the tone at this intensity on two consecutive occasions (to ensure at least a "two-out-of-four" response). Reduce the intensity of the signal in 5 dB steps, giving two, three or four presentations of the test tone (according to the number required for the "two-out-of-four" response criterion) at each intensity. In this way, the *descending threshold* is determined, i.e. the lowest intensity at which the subject is able to respond correctly on at least two out of four occasions, when the signals of about 2 sec duration have been presented at decreasing intensities beginning from a suprathreshold value.

(4) When the tone is no longer heard on four consecutive presentations at the particular intensity, increase the intensity in 5 dB steps until the subject responds to two out of four test tones. This is the *ascending threshold*. If the ascending and descending thresholds differ from each other, these values are recorded and the mean of the two readings is taken as the threshold at that particular frequency. In the majority of cases, the two thresholds are identical.

Testing should commence with a test tone at 1 kc/s, since Witting and Hughson

(1940) found that the smallest percentage of errors on repeated testing occurred at this frequency. Moreover, deafnesses usually first show themselves at one or other end of the frequency scale. Furthermore, a 1 kc/s tone is more easily recognizable than tones of either low or high audio-frequencies. The thresholds at the other frequencies are then tested, and at the end the threshold at 1 kc/s is checked. Inspection of Burns and Hinchcliffe's (1957) results indicates that an average error of about 2 dB may occur at 1 kc/s if the threshold is not checked. A lowering of threshold at 1 kc/s at the second test for the first ear tested was confirmed by the 1954 Wisconsin State Hearing Survey (Glorig *et al.*, 1957). This effect is presumably attributable to a learning process. The full sequence is therefore 1, 2, 3, 4, 6, 8, 0·5, 0·25, 0·125 and 1 kc/s. In industrial audiometry, the two lowest frequencies may be omitted.

(*c*) *Reliability of audiometry*

This point was extensively investigated by Brown (1948). For the same pure-tone audiometer and the same operator, the test-retest reliability was of the order 0·95 and the standard deviation of the difference between the two tests ranged from about 5 dB for the lower frequencies to about 7 dB for the higher frequencies. When the test was repeated by a different operator, there was no significant change in either the reliability or the standard deviation.

There was no significant difference between the results obtained by a fully-trained audiometrician and one who had previously tested only 30 subjects. This indicates that a person who is reasonably intelligent and sufficiently interested can become proficient after testing only 30 people. Glorig and Harris (1957) contend that an industrial audiometrist can be trained in 6–8 hr. After 2 hr lecturing on the anatomy and physiology of the ear, the fundamentals of psycho-acoustics, the audiometer and the importance of a hearing conservation programme, the rest of the time is spent on actual hearing testing.

4. PSYCHOLOGICAL FACTORS

(*a*) *Attitude of the observer*

The ability to concentrate, or Titchener's (1924) attensity factor, differs amongst individuals, and this might account for inter-individual threshold differences. Maire and Zwislocki (1956) claim that motivation may produce a 6 dB improvement in the auditory threshold.

(*b*) *Learning*

Brown (1948) found no improvement in the auditory threshold at the second test, although Maire and Zwislocki (1956) found an improvement of 4 dB in the auditory threshold at 100 c/s after six weekly tests, using a Békésy method; most of the improvement occurred at the second test. There is a smaller improvement for higher frequencies. Burns and Hinchcliffe (1957) found a 1 to 2 dB lowering of the threshold on a second test, for the range 500–4000 c/s, but the improvements were of marginal significance value only.

5. PATHOLOGICAL FACTORS

Although, when the other groups of factors are controlled, audiometry is most commonly employed to investigate the incidence and/or degree of this group of

factors, not infrequently the factors in the other groups are investigated when this group must be controlled.

The incidence of hearing defects is dependent on the nature of the population and which frequencies are taken into consideration. The 1954 Wisconsin State Fair Hearing Survey (Glorig *et al.*, 1957) showed that, for the speech frequency range 500–2000 c/s, the percentage of people with a hearing loss of more than 25 dB rose from about 3 per cent for people in the third decade to about 30 per cent for people in the seventh decade of life. In industrial populations, the incidence will also be proportional to the degree to which the environmental noise spectrum exceeds the Damage Risk Criterion (see Littler, 1958).

The investigation of hearing defects and their nature is an audiologic problem involving the anamnesis, a clinical examination and diagnostic audiometry, together, perhaps, with other special investigations, such as X-rays and vestibular function tests.

On a systematic basis, the anamnesis can be obtained by a questionnaire. The audiologic questionnaire used by us is shown in Appendix 2 and is a modification of Glorig and Quiggle's (1956) Hearing Conservation Data Card. A similar. self-answering questionnaire has worked satisfactorily (Ward, 1957). Ward also found that, when the same information was asked in an interview, the results were only rarely in disagreement. One can therefore infer that observer error is probably insignificant for the audiologic questionnaire.

The commoner abnormalities disclosed on clinical—essentially an otoscopic—examination are cerumen and scarred or perforated tympanic membranes. In a total population of 2550 school children who were audiometrically tested without a prior otological examination, Falbe-Hansen (1954) found that the incidence of hearing defect due to cerumen was less than 2 per cent. Most infrequently, impacted wax may give an overall loss of 40 dB, with the audiogram sloping downwards moderately towards the high frequencies (Saltzman, 1949). We have found that 6 per cent of the ears of males aged 18 to 24 years inclusive in a random sample rural population are completely occluded by wax. In a certain textile factory, however, we found that this incidence of meatal occlusion by wax was appreciably higher, i.e. about 15 per cent. Moreover, Behne (1956) found that 40 per cent of carding-machine sharpeners who had hearing defects also had plugs of cerumen, the formation of which had been promoted by the oil-saturated dust contained in the air of the spinning mills. Glorig *et al.* (1957) investigated the influence of otological abnormality on the hearing parameters of a general population. The median hearing loss at 1 kc/s for the total male sample was not altered when people with a history of exposure to audiologic hazards and/or abnormal otoscopic appearances were excluded. Moreover, the median hearing loss at 4 kc/s fell by about 5 dB only. Furthermore, this difference did not increase with age. One must infer that a major factor (or factors) responsible for hearing defect which increases with age is a condition (or conditions) which is not indicated by the usual audiologic questionnaire and is not evidenced by otoscopic abnormalities. This factor is the ageing process. The condition is known as presbycusis. Different people are affected to varying degrees by this ageing process, and reported representative values also vary considerably. For the threshold of hearing at 4 kc/s, both the United States Public Health Service National Health Survey 1935-36 and the 1954 Wisconsin

State Fair Hearing Survey indicate that there is a deterioration of about 40 dB from the age of 20 to the age of 60 years, whereas ROBINSON and DADSON (1957) imply that this value is nearer to 12 dB. The sampling problem in hearing surveys has recently been commented on by O'NEILL and GRIMM (1958).

A correction for this ageing process must be applied to audiograms taken in industrial hearing conservation programmes. In these industrial surveys, precautions must also be taken to eliminate, or if this is not possible, to minimize, the factor of temporary noise-induced hearing loss.

The degree of T.H.L. (= temporary hearing loss) depends on the intensity of the noise to which the subject was exposed, and its spectrum and character, the duration of exposure and the degree of auditory protection afforded, if any. NOVIAJSKI (1938) also showed that T.H.L. is greater in individuals previously exposed to the protracted influence of noise.

The *Guide for Conservation of Hearing in Noise* (1957) says that a preceding 16 hr period that has been free from noise exposure is an adequate safeguard against including T.H.L. in industrial hearing tests. Nevertheless, exposure to a continuous noise of 123 dB overall S.P.L. and for a duration of 12 hr may produce T.H.L. from which recovery is not complete for $3\frac{1}{2}$ days (HINCHCLIFFE, 1955). Moreover, in a recent report on the hearing of naval aircraft maintenance personnel who are exposed to noise intensities above 140 dB S.P.L., WARD (1957) stated that, although he would prefer an even longer rest, the 16 hr criterion was the best compromise between scientific accuracy and operational expediency. However, noise levels currently encountered in industry are much lower than these, so that, in general, recovery from auditory fatigue should be complete by the time the operative is ready to start work again after the week-end break. It is probable, too, that, in the majority of noisy industries, any noise-induced temporary hearing loss disappears overnight. Audiometric tests should therefore be given at the beginning of the working day, before work is started, or, preferably, on a Monday morning.

The interpretation of individual audiograms regarding occupational hearing loss and the assessment of the degree of this loss will not be discussed here, since it forms the subject of an accompanying paper (HINCHCLIFFE, 1958).

Sometimes, in air-conduction audiometry, masking of the ear not being tested will be required to prevent the test tone stimulating the ear not being tested.

When a sound stimulus is applied to one ear by an air-conduction receiver, the sound field in the external auditory meatus excites the skull by bone conduction and, if sufficiently intense, may stimulate the opposite cochlea. This is known as cross-hearing and may be responsible for erroneous audiometric results whenever at any frequency there is a difference greater than 40 dB between the air-conduction threshold of one ear and the bone-conduction threshold of the opposite ear. In perceptive type hearing losses, this difference can be considered to be the difference between the two air-conduction thresholds at any frequency. But it cannot be considered so in conductive deafnesses or cases in which there is a conductive loss on one side and a perceptive loss on the other. The audiometric Weber (MARKLE *et al.*, 1952) and Schwabach tests together with the Bing or occlusion test (LITTLER, 1954) will indicate the type of deafness, so that the air-conduction thresholds must be reviewed after these tests have been performed. However, if during the course of

determining the air-conduction threshold, a difference of more than 40 dB is indicated between the two air-conduction thresholds at any frequency, then the poorer ear must be retested whilst the better ear is masked. The masking level must be sufficient to mask that ear, but insufficient to cross-mask the ear under test. In general, masking levels up to 70 dB applied to the better ear will cover most cases but, if the subsequent qualitative and quantitative bone-conduction tests indicate an element of conductive hearing loss in either ear, the masking must be reconsidered. For a pure unilateral conductive deafness, a 40 dB masking level applied to the normal side is appropriate.

CONCLUSIONS

As LENIHAN (1957) says, an audiometer will give reliable indications only if its output remains constant within limits much closer than those normally specified for electro-acoustical equipment. Audiometers are subject to all the faults occurring in electronic apparatus. Only full and frequent calibration together with careful monitoring in the manner that we have described will ensure adequate instrumentation. Not infrequently, however, audiometers remain in close calibration for two or three years (WATSON and TOLAN, 1949).

Adequate instrumentation and a testing procedure that follows the pattern which we describe will form the basis of acceptable air-conduction threshold audiometry.

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APPENDIX 1

MOBILE AUDIO TEST CHAMBER

SOME DETAILS OF MATERIALS AND CONSTRUCTION

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Pneumoconiosis Research Unit

Materials

THE aim was to achieve a sufficiently high sound attenuation, without making the walls too thick, thereby making the inner test chamber smaller; and, of course, the weight factor had to be kept in mind.

The layers of various materials starting from the outside were as follows:

1. *"Issoflex"*

The body structure was formed with 3 in. × 2 in. hardwood framing, sheeted on the outside with metal, and hardboard on the inside, and the cavity filled with Issoflex, a cellulose insulating material.

2. *1 in. "Paxfelt"*

Weight: 12 oz. per ft^2, 1 in. thick.

Frequency (c/s)	250	500	1000	2000
Sound absorption (per cent)	50	55	65	70

To the inside of the original body a 1 in. layer of "Paxfelt" was applied all over the sides and roof, secured with wide, thin battens.

The floor of the van was made of 6 in. × 1 in. tongue and grooved floor boarding covered with ¼ in. cork lino. (The wheel arches were situated roughly in the middle.) The ends were sealed off and filled with 7 in. of granulated cork. Over this, making the whole floor of the test chamber area level, ½ in. "Weyroc" was laid.

½ in. "Weyroc"

This material has a density of 2 lb per ft^2. An N.P.L. report gave the average attenuation over the range of 200–2000 c/s as 27 dB.

1 in. Fibre-glass

Over the "Weyroc" sub-floor two thicknesses of 1 in. fibre-glass were laid in opposite directions.

Formation of the Inner Chamber

The outer skin was formed with ½ in. high-density "Weyroc," covered with "Synthapruf," and, while still wet, granulated cork was scattered all over it. This was intended to seal the outer skin completely.

"Stramit"

Average sound attenuation of 2 in. thickness over range 200 to 2000 c/s = 29 dB.

This is a compressed strawboard impregnated with plaster, which has good mechanical properties.

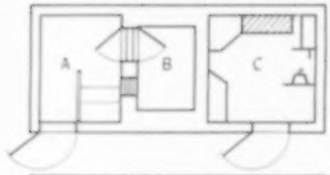
Next to the ½ in. "Weyroc" outer skin, and allowing ½ in. air space, a layer of 2 in. "Stramit" was laid. On this, separated by another ½ in. air space, was the final cover of 1 in. "Paxtile."

This is a perforated sound-absorbing asbestos made in 1 ft 6 in. squares and at 1600 c/s has an absorption ratio of 85 per cent.

Floor

Dunlop Anti-vibration B Series Mountings

The whole of the inner shell was supported on four special mountings, made by Dunlop. These were secured to the van floor, resting on the fibre-glass layers and bolted through the floor.



ROOM	HEIGHT	WIDTH	LENGTH
A	7'-7"	7'-0"	5'-0"
B	5'-10½"	5'-7½"	4'-6"
C	7'-7"	7'-0"	6'-7½"

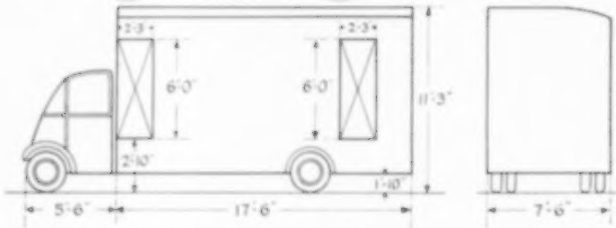


FIG. 1. Plan of mobile audio test chamber.

FIG. 2. Plan of test chamber.

These mountings supported a metal frame which formed the base of the inner chamber. To the top of this metal frame a layer of $\frac{3}{4}$ in. high-density "Weyroc" was bolted down and covered over with Flexible Asbestos Felt, which has an average sound attenuation of 65 per cent.

Doors

The two doors were Thames type, straw filled, faced on their respective outsides with 1 in. "Paxtile," and on the inner with $\frac{1}{2}$ in. insulation board. Rubber seals were attached to the doors and an absorbent cavity between doors.

Windows

The observation window was made up of four panes of glass of different thicknesses 8 mm and 15 mm, and measured 1 ft square.

It was estimated that the test chamber gave a sound reduction factor of about 40 dB.

APPENDIX 2

QUESTIONNAIRE RE AUDIOLOGIC HAZARDS

A.

Name .... Address .... Date of Birth ....

Sex .... Serial No. ....

B. CURRENT NOISE EXPOSURE

1. What is your job?
2. At any time in this job, is it ever so noisy that you have to raise your voice to be heard?
3. For how many hours of the week is this so?
4. How long have you been in this job?
5. Do you ever wear any ear protection?
   (i) Always or frequently?
   (ii) Seldom or never?
6. What ear protectors do you use?

C. PREVIOUS NOISE EXPOSURE

I. *Occupational*

1. Prior to your present job, have you ever worked in a noisy industry where you had to raise your voice to be heard?
2. If so, did you work in a noisy job for more than one year?
3. What jobs and for how long?
4. Did you use ear protectors?
   (i) Always or frequently?
   (ii) Seldom or never?
5. What ear protectors did you use?

II. *Other Acoustic Trauma*

1. Have you ever used a rifle or other guns?
2. If so, was it a 0·303?
   12-bore (Specify)
   or other guns?
3. Did you use any ear protectors?

D. MOST RECENT NOISE EXPOSURE

1. How long is it since you last had to raise your voice to be heard because it was so noisy?
2. What was the duration of this particular noise exposure?
3. Did you use any ear protectors?

E. OTHER AUDIOLOGIC HAZARDS

1. Have you ever had/do you ever have pains in the ears?
   (i) When?
   (ii) Which ear?

2. Have you ever had/do you have running ears, discharge from, or abscesses in, the ears?
    (i) When?
    (ii) Which ear?
3. Have you ever had an injury to the ear?
    (i) What?
    (ii) When?
    (iii) Which ear?
4. Have you ever had an operation on the ear or the mastoid, or has the ear-drum ever been punctured?
    (i) When?
    (ii) What?
    (iii) Which ear?
5. Have you ever had an injury to the head which made you unconscious?
    (i) When?
    (ii) How long unconscious?
6. Have you ever noticed noises in either your ears or your head?
    (i) Did this occur before you were first exposed to noise?
    (ii) If not, how long was it after first being exposed to noise?
7. Do you suffer, or have you ever suffered, from giddness or dizziness? i.e. you actually felt as though you or the room were going round. (N.B. Exclude other than hallucinations of movement.)
8. To your knowledge, have you ever had injections of streptomycin?
    (i) When?
    (ii) For how long?
9. To your knowledge, have you ever had quinine?
10. Have you ever had any of the following illnesses?
    Mumps
    Meningitis
    Rheumatic fever
    Malaria
11. Is there any deafness in the family?
    (i) Who?
    (ii) Deafness began at what age?

F. Present State of Hearing

1. How is your hearing?
    (i) Normal
    (ii) Not as good as it should be — Fair / Poor / Very Poor
2. If there is a particular incident of any sort that you think might have damaged your hearing (for example, an explosion, a blow on the ear, or such like), please describe the incident, mentioning about how long ago it happened.

G. PREVIOUS AUDIOMETRY

1. Have you ever had your hearing tested with a machine before?
2. If so:
   - (i) When?
   - (ii) Where?

H. CERUMEN

1. Have you ever had your ears syringed to remove wax?
2. If so:
   - (i) When?
   - (ii) Which ear?

PAPERS TO BE PUBLISHED IN THE NEXT ISSUE

F. M. Englebrecht and R. Paul: Enzymes in the development of silicotic fibrosis in the lungs of rats.

J. W. J. Fay and S. Rae: The pneumoconiosis field research of the National Coal Board.

A. Arnulf, J. Bricard, R. Burtin and C. Veret: The determination of the particle size distribution in clouds of liquid drops suspended in air by means of direct photography.

F. G. M. Seager: Some observations on the incidence and treatment of back injuries in industry.

P. Chavasse, G. Saulnier *et* H. Nickles: Protection des travailleurs contre les bruits et les vibrations.

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ENZYMES IN THE DEVELOPMENT OF SILICOTIC FIBROSIS IN THE LUNGS OF RATS

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INTRODUCTION

CURRENT opinion assumes that silicosis is due either to the chemical effects of quartz (silica solubility) or to the physical adsorption of biological substances on to the surfaces of quartz (surface activity of particles). Neither of these theories fully explains the fibrotic response to the introduction of siliceous matter into lung tissues, and many aspects of the pathogenesis of the silicotic nodule remain unsolved.

The adsorption phenomena of the dust particle surfaces have been studied extensively. Particulate silica in the form of quartz is known to adsorb proteins, such as egg albumin, bovine albumin and fibrinogen from solutions (DALE and KING, 1953; SCHEEL *et al*, 1954; and HOLT and BOWCOTT, 1954). Not only protein substances were adsorbed but also dyes, amino aicds and metal hydroxides (DALE and KING, 1953). KOCH (1949) and NEU (1951) postulated the adsorption of a specific fat-protein complex on to the silica particle in developing silicosis, while HOLZAPFEL (1952) produced evidence for the adsorption of galactose and cholestreol. CLAYS and GUINOT (1954) were of the opinion that a complex between carbon dioxide and the quartz surfaces was formed. LUHNING (1954) claimed that the polysilicic acid has precipitation effects on lung proteins and especially on the erythrocytes.

VIGLIANI (1958) suggests that the hyaline tissue of silicotic nodules has an immunological origin; that quartz particles penetrate into the organism, adsorb organic substances and orientate them so that they become auto-antigens, subsequently inducing formation of auto-antibodies. The hyaline substance of silicotic masses and nodules is considered to be a result of formation of local antibodies and precipitations on antigens and on newly-formed reticulin fibres.

In vitro studies of the action of quartz and other mineral dusts on enzyme activity showed that most enzymes are adsorbed on the particle surfaces. KING *et al.* (1953) demonstrated that alkaline and acid phosphatase are adsorbed specifically. HELFERICH and SCHMITZ (1953) found that quartz as well as aluminium phosphate adsorbed the phosphatases of potato, but trials on silicotic lung tissue gave negative results. SCHUMACHER (1953) showed specific adsorption of lysozyme to quartz surfaces. DANIEL-MOUSSARD (1955) studied the *in vitro* action of silica on the activity of ribonuclease, because of the important rôle of this enzyme on the metabolism of the cell, without any positive results. BAUMANN (1955) found that quartz, aluminium phosphate, iron carbonate and coal, all adsorbed hyaluronidase, esterase and lipase. Because of the variable results obtained with esterase he concluded that an inhibitor for this enzyme system was adsorbed on to quartz surfaces.

Not only particulate silica but also silica in solution (colloidal silica) may influence enzyme systems. HUBNER (1952) postulated the inhibition of hyaluronidase by colloidal silica and also the formation of sugar from starch by diastase. KING *et al.* (1956) found that silicic acid inhibits prostatic acid phosphatase and erythrocyte acid phosphatase, but no inhibition could be demonstrated with alkaline phosphatases. JAMES and MARKS (1956) found a marked inhibition of cytochrome C oxidase. ROWSELL (1958) found that polysilicic acid increased the respiration of liver homogenates with fumurate, but not of liver slices.

The association of enzymes with the process of reticulin fibre formation in the pathological state is still controversial. DANIELLI (1946), after an investigation on the kidney, concluded that phosphatase activity is never localized in the cytoplasm of cells except in regenerating tissues; and is somehow associated with fibre formation. But ROBERTSON *et al.* (1950), in repeating and extending the work of FELL and DANIELLI (1943), and DANIELLI *et al.* (1945) could find no evidence to support an association of alkaline phosphatase with fibre formation. Many authors contributed to this dispute, e.g. JOHNSON *et al.* (1945) and JENNER (1947). Only GOLD and GOULD (1951) and GOULD and GOLD (1951) produced evidence for such a relationship. However, no attempt was made until recently (COLLET and DANIEL-MOUSSARD, 1956) to study the relation between enzymes and silica (in solution, particulate or colloidal) in the process of fibre formation in silicosis.

Experiments were therefore planned to investigate the pathogenesis of the silicotic nodule and to correlate the pathology with enzyme activity in lung tissue. To demonstrate the enzyme activity, if any, histochemical techniques were applied to silicotic lung tissue. In another experiment, chemical methods for the enzymes were performed to establish whether there was any correlation between the chemical and histochemical findings on silicotic lung tissue.

MATERIAL AND METHODS

Animals

The rats used in these investigations were the black and white piebald variety of the Medical Research Council strain. They were all males of average weight 150–200 g. Thirty-six animals were divided into a control group and two experimental groups of twelve animals each respectively. The animals in the experimental groups were injected with a tridymite suspension intratracheally, and killed at set time intervals. In one group the concentration of different enzymes was estimated chemically, while in the animals of the other group the enzyme localization in silicotic lung tissue was demonstrated histochemically.

Preparation of the dust suspension

Tridymite (X 2285) with particle size 0·5–2μ was used to induce the pathology in the lung tissue. 0·75 g of dust was weighed out, transferred to a tissue grinder and ground with 30 ml of 0·85 per cent saline (1 ml = 25 mg). One millilitre of suspension was injected into the lungs of each animal through the trachea according to the technique of KING *et al.* (1953).

Histological technique

The animals in this experiment were killed at 0, 24, 48 hr and 4, 7, 14, 21, 28, 42, 56 and 70 days after the injection of the suspension. The animals were killed by a blow

on the head, the trachea exposed and the lungs distended by the injection intratracheally of 10 ml cold (4°C) 10 per cent formalin in 1 per cent $CaCl_2$, pH 7. The lungs were quickly dissected out, and immersed in cold fixative in an ice box at 4°C for 16 hr. Suitable tissue blocks, cut through the long axis of the lung, were selected from the left lobe of each lung and further prepared in the routine manner, embedded and cut in paraffin. Sections were made serially and stained with GORDON and SWEET's (1936) silver impregnation for reticulin and with haematoxylin and eosin for normal histology.

Tissue blocks for frozen sections were selected from the remnants of the left lobe as well as from individual lobes of the right lung and washed for 2 hr in 0·85 per cent cold saline (4°C) in an ice box. Frozen sections 30μ thick were made of each lobe, mounted on clean slides and left to dry at room temperature for 1 hr. The slides were left in an ice box at 4°C until enzyme reactions were performed.

Histochemical methods

The standard histochemical azo-dye methods were performed for alkaline phosphatase, acid phosphatase and non-specific esterases (PEARSE, 1953). For sulphatase, the method of RUTENBERG *et al.* (1952) was used.

The alkaline phosphatase method (PEARSE, 1953)

This method was used for both frozen and paraffin sections. Sodium α-naphthyl phosphate, 1 mg/ml, was used as substrate and as coupling reagent the diazotate of 4-benzoyl amino 2: 5 dimethyloxyaniline (salt 2) 1 mg/ml in 0·1 M veronal acetate buffer, pH 9·2. The solution was well shaken and filtered on the slides and incubated at room temperature (18°C) for 15 min. Sections were then well washed in running water for 3 min and mounted in glycerine jelly. The sites of alkaline phosphatase activity are coloured black with this method and salt.

The acid phosphatase method (PEARSE, 1953)

This method gives good results only on frozen sections of lung tissue. As substrate, sodium α-naphthyl phosphate (1 mg/ml) was used with the diazotate of O-dianisidine (Fast Blue Salt 6) as coupling reagent in 0·1 M veronal acetate buffer, pH 5. The solution was well shaken and filtered on to the slides and incubated for 60 min at room temperature. Slides were well washed in running water and mounted in glycerine jelly. The sites of acid phosphatase activity are coloured purplish-red with nuclei deep blue.

The non-specific esterase method (PEARSE, 1953)

This method was used on paraffin and frozen sections. 20 mg of the substrate α-naphthyl acetate was dissolved in 0·25 ml acetone and well mixed with 20 mg O-dianisidine (Fast Blue Salt 6) in 20 ml of 0·1 M phosphate buffer pH 7·4. The solution was filtered on to the slides and incubated for 5 min at room temperature. The slides were well washed in running water for 3 min and mounted in glycerine jelly. Sites of esterase activity are coloured black with nuclei dark blue.

The sulphatase method (RUTENBERG *et al.*, 1952)

This method was performed only on frozen sections. Paraffin sections showed no activity. The sections were incubated in substrate solution of potassium-6-benzoyl-2-

naphthylsulphate. Twenty-five milligrammes of substrate was dissolved by heat in 80 ml of 0·85 per cent saline. To this was added 20 ml of 0·5 M acetate buffer, pH 6·1. This substrate solution was made hypertonic by adding 2·6 g NaCl to each 100 ml of solution. Slides were transferred to coplin jars in this incubation medium at 37°C for 16 hr. Sections were then washed in two baths of cold 0·85 per cent saline for 30 min. After the washing, the sections were transferred to a freshly-prepared solution of tetrazotized O-dianisidine (1 mg/ml) in 0·05 M phosphate buffer, pH 7·6 for 5 min. They were then washed three times in cold 0·85 per cent saline and finally in water for 15 min each and mounted in glycerine jelly. Areas of high sulphatase activity stain blue to purple, while areas of low activity are coloured red to purple.

CHEMICAL METHODS AND TECHNIQUES

General procedure

Twenty-four animals were used for the chemical investigation. The control group consisted of twelve animals and the experimental groups of twelve animals which were injected with a tridymite suspension as previously described. One animal from each group was killed at the same time interval as for the histochemical investigation. The animals were killed by a blow on the head, the lungs dissected out as quickly as possible, weighed and immediately transferred to an ice box at 0°C. The lungs were homogenized within 30 min in 0·85 per cent sodium chloride solution with a Waring Blender at 0°C. The initial dilution of the suspension was 1 g of tissue in 50 ml sodium chloride solution.

Chemical methods

The following chemical determinations were done in duplicate on the lungs of normal and silicotic rats; alkaline phosphatase, acid phosphatase, esterase, sulphatase and collagen.

To two test tubes each were added 2 ml buffer solution and 2 ml substrate and heated for 5 min at 37°C. Then homogenate was added and incubated. Folin and Ciocalteu's Reagent (one-third dilution) was added in such amount that the final volume was 6 ml. The tubes were mixed and centrifuged. Blanks were prepared in the same way, except that the homogenate was omitted until after the addition of Folin and Ciocalteu's Reagent. Four millilitres supernatant were removed from each tube and mixed with 2 ml Na_2CO_3 (15 per cent w/v) and heated for 15 min at 37°C. Colour development was measured in an Eel photoelectric colorimeter, using Ilford filter 608, and compared with standards prepared in the following way.

Stock standard phenol solution. This was prepared by dissolving 1 g phenol crystals in 1 l. 0·1 N-HCl (1 mg/ml) and from this a diluted phenol solution containing exactly 10 mg of phenol per 100 ml was made up.

Standard-phenol-solution-and-reagent. To 1 ml of diluted phenol solution add 6 ml of distilled water and 3 ml of diluted Folin and Ciocalteu's Reagent. Prepare shortly before use (0·01 mg phenol/ml).

Preparation of standard. To 1 ml standard-phenol-solution-and-reagent (0·01 mg/ml) was added 1 ml of distilled H_2O and 2 ml buffer solution followed by 2 ml of 15 per cent sodium carbonate and incubated with the blank and unknown in a water bath for 15 min at 37°C.

The details for each individual method are noted below:

Alkaline phosphatase (King, 1951)
M/100 disodium phenyl phosphate substrate
M/10 sodium carbonate-bicarbonate buffer, pH 10
0·2 ml homogenate of 1/50 dilution
Incubation time 15 min at 37°C.

Acid phosphatase (King, 1951)
M/100 disodium phenyl phosphate substrate
Citric acid buffer, pH 4·9
0·2 ml homogenate 1/50 dilution
Incubation time 60 min at 37°C.

Esterase (Nachlaus and Seligman, 1949)
M/20 α-naphthyl acetate substrate dissolved in 0·25 ml of acetone and diluted to a working solution of M/200 in distilled water
M/15 phosphate buffer, pH 7·0
0·2 ml homogenate 1/200 dilution
Incubation time 15 min at 37°C.

Sulphatase (Boyland, personal communication)
M/100 nitro catechol sulphate substrate
0·5 M acetate buffer, pH 5·8
0·2 ml homogenate 1/50 dilution
Incubation time 60 min at 37°C.

Collagen (Stacy, 1955)
Collagen estimations were done on dried lung homogenate. The dry weight of lung tissue was determined by drying a known volume of homogenate and correcting for the weight of NaCl in that volume.

RESULTS

The histology of the developing silicotic nodule in the lung of the rat

Within 24 hr after the injection of 25 mg tridymite suspension into the lungs of a rat a violent tissue reaction was observed. This reaction consisted of a concentration of polymorphonuclear cells, especially eosinophils and mononuclear leucocytes, in those lung areas where the particulate material was deposited (Fig. 1). A thickening of the alveolar walls, dilatation of the capillaries and diapedesis of red corpuscles and exudation of proteinous material also occurred.

At 48 hr the intensity of the initial reaction was increased and already cellular dust concentrations were encountered. The general picture appeared to be one of acute inflammation. The silver impregnated sections at this stage showed a dense silver precipitation in the areas where cellular collections were found.

At the fourth day the cytological response was changed. In the central parts of the cell accumulations, a degeneration of practically all the polymorphonuclear cells occurred, the cytoplasm being so vacuolated as to give a foamy appearance. Fragments of nuclei were seen dispersed in a homogenous protein material (Fig. 2). The nodules appeared to consist of a central core of mainly protein material, including a large number of dust particles, and practically cell free. Only a few histiocytes and fibrocytes survived in these areas of severe necrosis. Presumably these cells are more resistant to the toxic effect of the tridymite particles. Immediately around the necrosed

central parts of the nodules an intermediate zone exists in which many histiocytes, fibrocytes and mononuclear cells were encountered. These cells which were not directly in contact with the dust particles showed slighter structural change. From the outer border zone, histiocytes could be seen advancing on the central disintegrated tissue masses. New growths of capillaries were also observed in the peripheral zone and occasionally slight haemorrhage occurred.

The pathology of the silicotic lung on the seventh day was quite different from that on the fourth. The degenerated homogenous material of the central core of the nodule, which contained a high concentration of dust particles, was penetrated by fibrocytes (Fig. 3). The cellular debris disappeared gradually and more reticulin fibres were formed linking one fibrocyte with another. By this fibrocyte and histiocyte infiltration from the bordering tissue, the central part of the nodule became nucleated again.

At this stage an increase in reticulin fibres was observed in the proximity of lymphoid tissue around the bronchi and also in areas where dust collections were found. In some of the latter areas, the normal reticulin structure appeared to be slightly damaged, and this phenomenon was always accompanied by a dense silver impregnation (Fig. 4). Well-defined nodules of reticulin were encountered in some lung areas and in the centre of these nodules collagen deposition was in process. In these more advanced nodules a slight silver precipitation was found only in the peripheral zones where many polymorphonuclear cells and macrophages were accumulated.

The outstanding feature marking the 14-day period was the dense collagen deposition in the centre of the nodules where a high concentration of dust particles was localized. As the collagen deposition advanced, the central core of the nodule became acellular (Fig. 5). Apparently the collagen deposition in the peripheral, cellular zone was retarded in comparison with the rate of deposition in the central parts where only

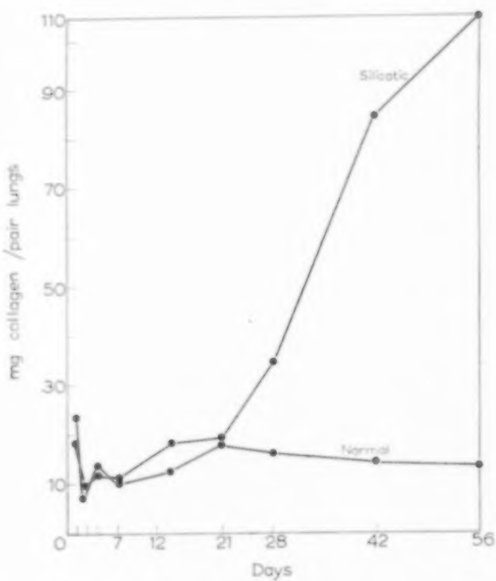

FIG. 6. Total lung collagen in normal and experimental animals injected with 25 mg tridymite.

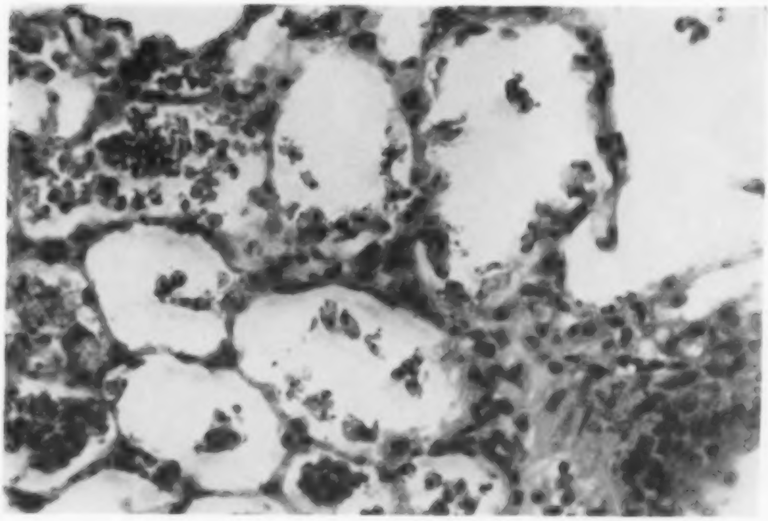

FIG. 1. Rat lung, one day after injection of 25 mg tridymite. Early stage of polymorphonuclear and mononuclear cell infiltration. Haematoxylin and eosin. ×430.

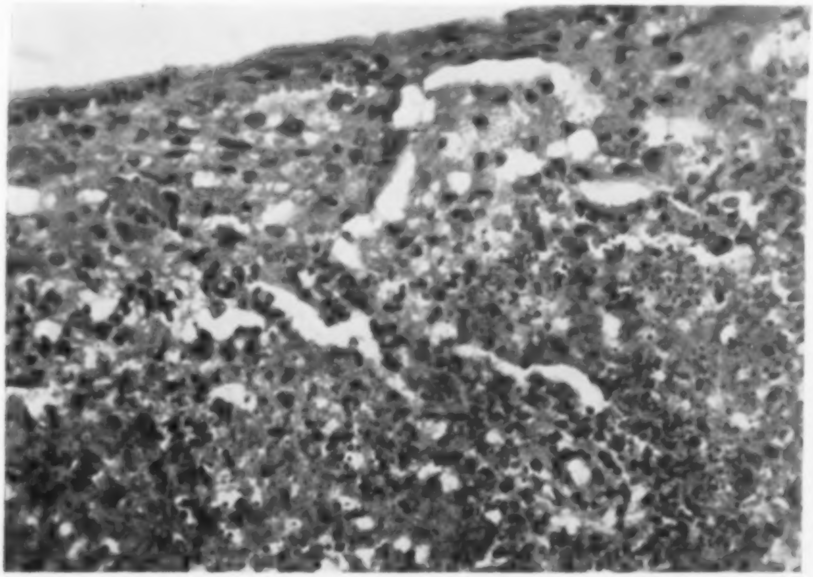

FIG. 2. Rat lung, 4 days after injection of 25 mg tridymite. Extensive degeneration in the central part of a cellular concentration. Haematoxylin and eosin. ×430.

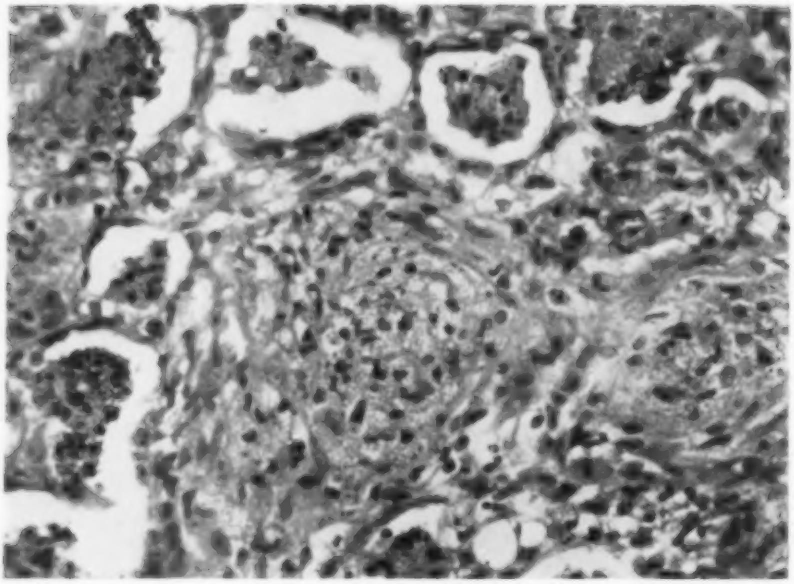

FIG. 3. Rat lung, 7 days after injection of 25 mg tridymite. Cellular lesions with a large amount of particulate matter and a few fibrocytes in the central areas of beginning nodules. Haematoxylin and eosin. ×430.

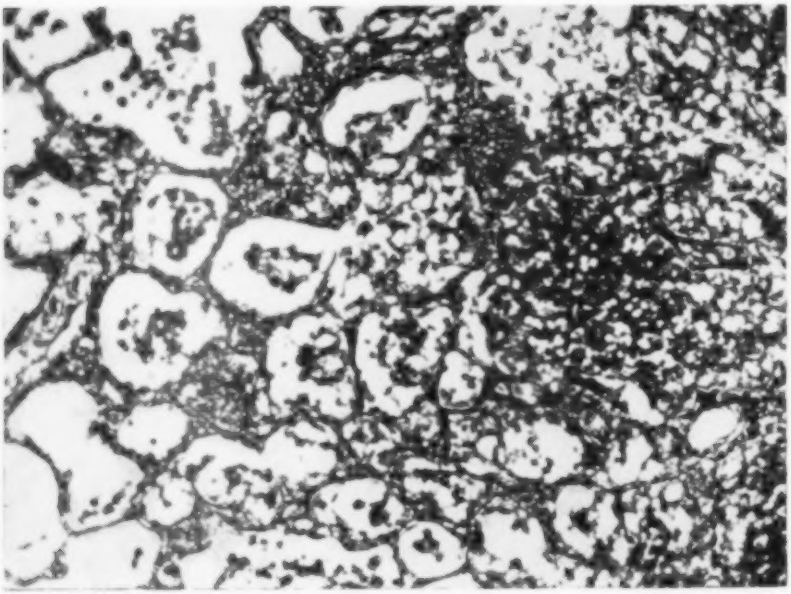

FIG. 4. Rat lung, 4 days after injection of 25 mg tridymite. Dense silver precipitate in degenerating area of cellular concentration. Silver impregnation. ×205.

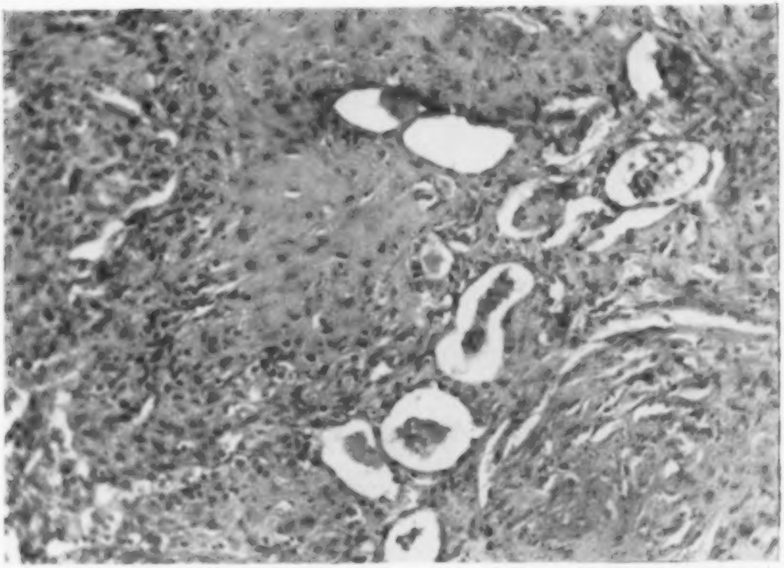

FIG. 5. Rat lung, 21 days after injection of 25 mg tridymite. Compact collagenous nodule becoming acellular in central area. Haematoxylin and eosin. ×205.

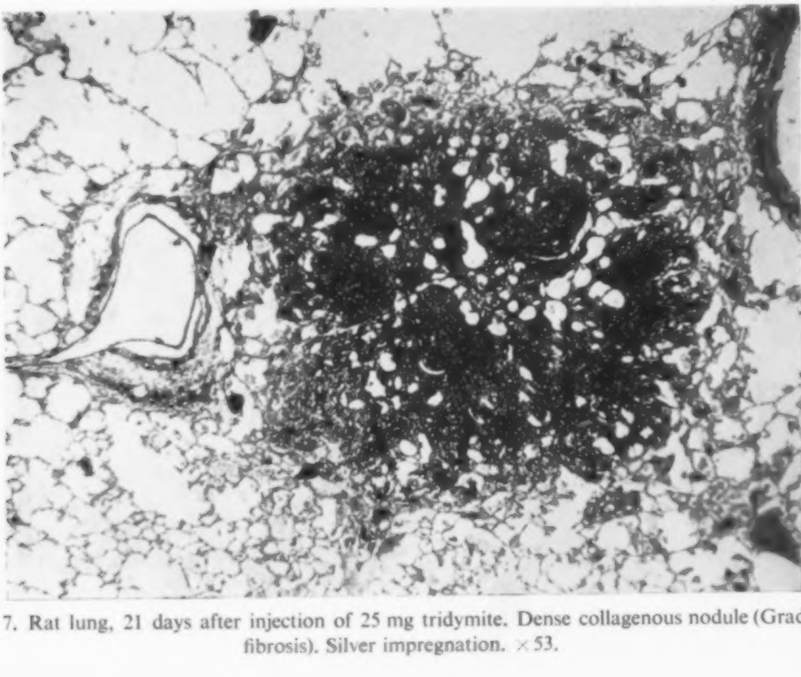

FIG. 7. Rat lung, 21 days after injection of 25 mg tridymite. Dense collagenous nodule (Grade IV fibrosis). Silver impregnation. ×53.

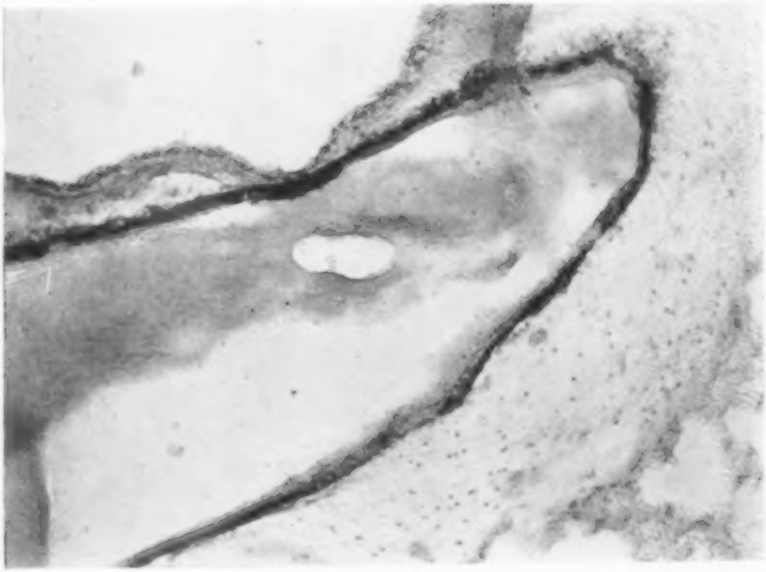

FIG. 8. Frozen section of rat lung, control animal, showing localization of alkaline phosphatase activity. ×90.

fibrocytes and histiocytes survived. At 14 days, grade II fibrosis* was reached and from this stage until the termination of the experiment, a steady increase in collagen deposition and maturation occurred (Fig. 6). As early as 42 days, Grade IV fibrosis was encountered (Fig. 7).

The histochemistry of the silicotic lung

Alkaline phosphatase. In normal lung tissue the alkaline phosphatase activity was localized in the arterial walls and mainly in the connective tissue layer (Fig. 8). During the early period, after the injection of the tridymite suspension, the localization remained the same. The concentration, however, increased, as was shown by the chemical estimations (Figs. 9a, b).

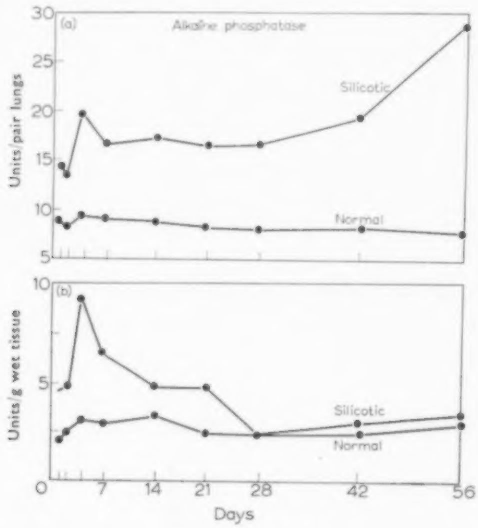

FIG. 9. Lung alkaline phosphatase activity of normal and experimental animals injected with 25 mg tridymite.

(a) Values are expressed as total units of activity per rat lung.

(b) As units of activity per gram wet weight of lung tissue.

At about the fourth day, during the period of acute inflammation, cellular degeneration and autolysis, a diffuse distribution of alkaline phosphatase activity was demonstrable in the peripheral zones of the cell concentrations (Fig. 10). The central, necrotic parts of the cell concentrations showed a less marked reaction and only a fine black precipitation was found in these parts. Also the nuclei of the leucocytes showed alkaline phosphatase activity at this stage.

From the seventh day, a relative decrease in the alkaline phosphatase activity was observed histochemically. In newly-formed blood vessels in the peripheral zones of the nodules, high activity persisted. The chemical findings, when expressed as units

* The histological grading of fibrosis, according to BELT and KING (1945), was as follows: "Grade I, loose reticulin and no collagen; Grade II, compact reticulin with or without a little collagen; Grade III, somewhat cellular but made up mostly of collagen; Grade IV, wholly composed of collagen fibres and virtually acellular; Grade V, acellular, collagenous, confluent".

of alkaline phosphatase activity per gram wet tissue, substantiated these histochemical observations, but when expressed as total activity per rat lung, no decrease in concentration was found up to the termination of the experiment. This is due to the increase in the total weight of the lung with tissue in silicosis.

Non-specific esterase

Normal distribution. In normal rat lung tissue the non-specific esterase activity was localized in the nuclei of the bronchial epithelial cells, septal cells and polymorphonuclear cells (Fig. 11).

During the one to two day period, a marked increase in the esterase activity was demonstrable in the cell concentrations. At about the fourth day, when disintegration of cellular elements was observed in the central parts of these cell concentrations, the esterase activity also vanished from these necrotic areas. High esterase activity, however, persisted in the peripheral zones (Fig. 12).

From the seventh day until the termination of the experiment, no further histochemical changes were observed as far as esterase activity was concerned. The high activity in the peripheral parts of the nodules may be due to a process of recanalization and the appearance of small lacunae, apparently an attempt to re-establish air sacs or passages which have been obliterated. These re-opened air spaces were lined by a conspicuous cuboidal epithelium which showed high esterase activity (Fig. 13).

The chemical data obtained from esterase determinations were variable and did not lend much support to the histochemical findings (Figs. 14a, b).

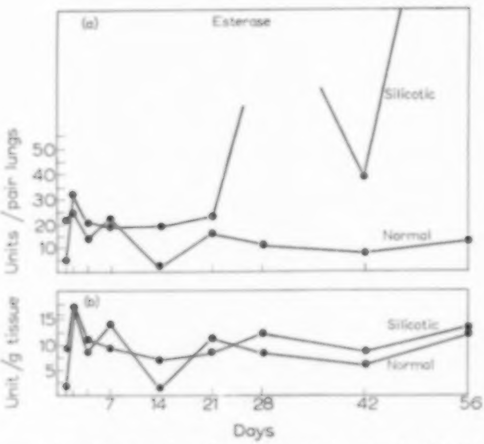

FIG. 14. Lung esterase activity of normal and experimental animals injected with 25 mg tridymite suspension.
(a) Values are expressed as total units of activity per rat lung.
(b) As units of activity per gram wet lung tissue.

Acid phosphatase

Normal distribution. In normal rat lung tissue, acid phosphatase activity was localized in the bronchial epithelium, walls of the blood vessels and lymphoid tissue. Because of the association of acid phosphatase activity with the capillary network, a

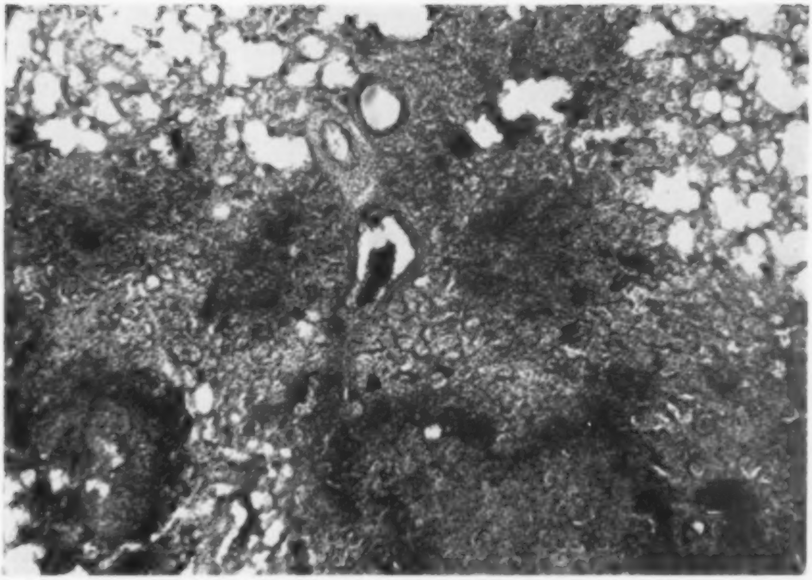

FIG. 10. Frozen section of rat lung, 4 days after injection of 25 mg tridymite. Diffuse alkaline phosphatase distribution in degenerating tissue. ×40.

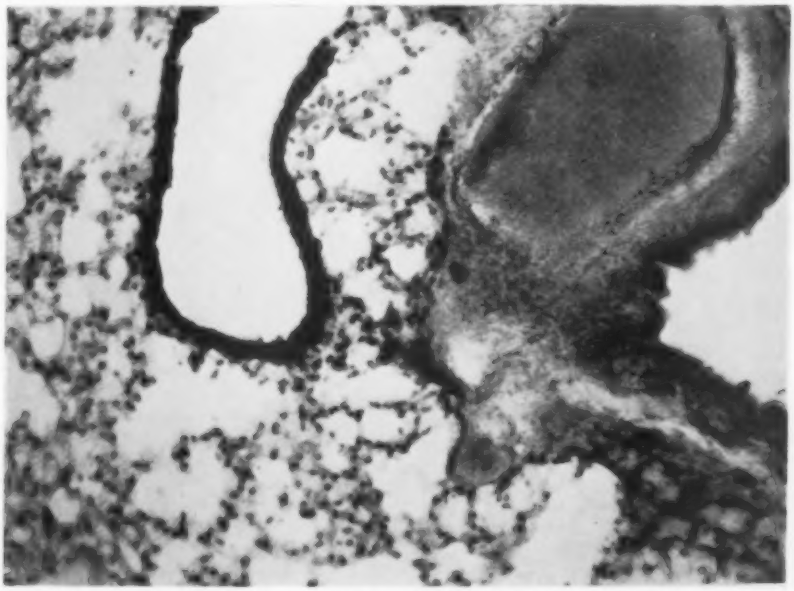

FIG. 11. Frozen section of rat lung, control animal, showing localization of non-specific esterase activity. ×90.

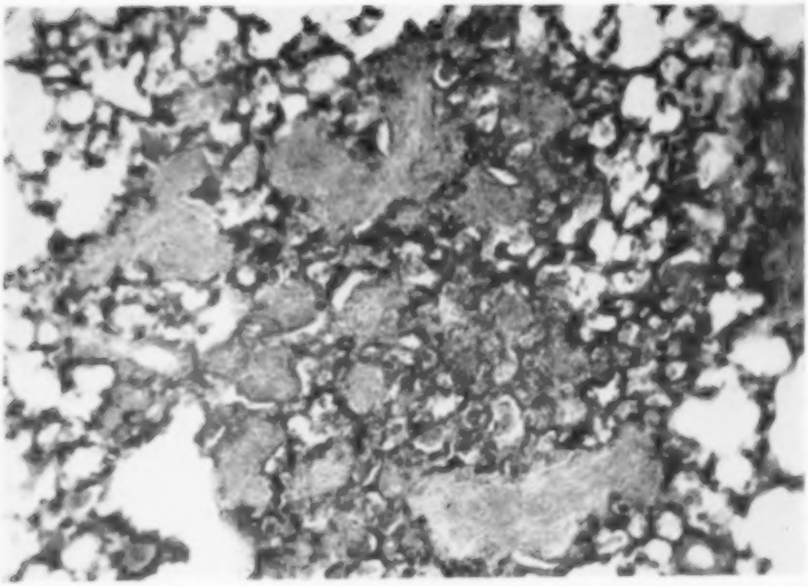

FIG. 12. Frozen section of rat lung, 7 days after injection of 25 mg tridymite, with no non-specific esterase activity in centre of nodules. ×90.

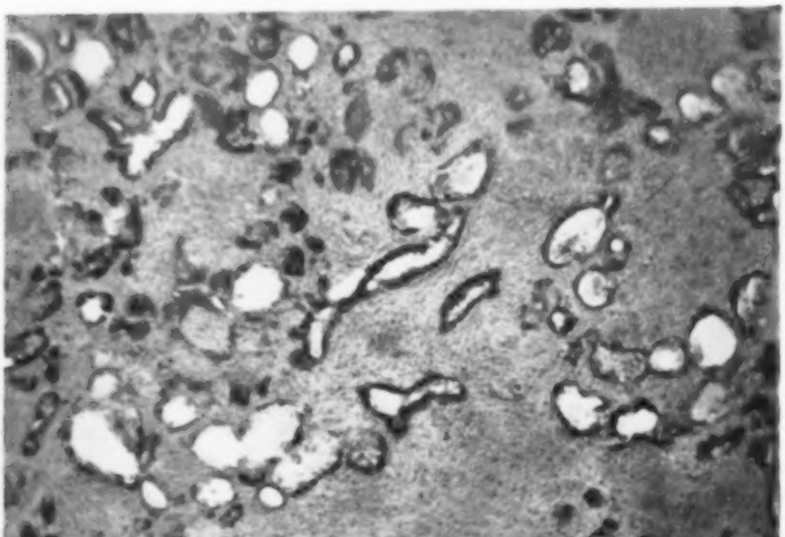

FIG. 13. Frozen section of rat lung, 14 days after injection of 25 mg tridymite. Compact nodule of collagen with openings lined by cuboidal epithelium, showing high esterase activity. ×90.

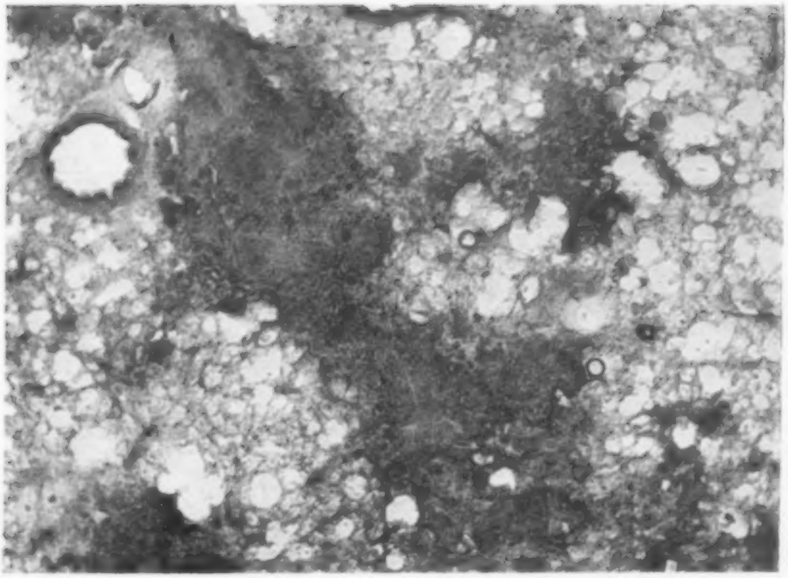

FIG. 15. Frozen section of rat lung, 7 days after injection of 25 mg tridymite; showing localization of acid phosphatase to cellular concentrations. ×40.

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slight background staining was obtained in the normal lung sections. No nuclear elements were stained.

In the early stages of the experiment up to 4 days, it was difficult to recognize a definite increase in acid phosphatase activity. The cell concentrations, however, showed a slight increase in colour intensity in comparison to the faint background staining.

At the 7 day period, a considerable increase in acid phosphatase activity was demonstrable in the dust cellular concentrations (Fig. 15). The chemical results substantiated this observation when the acid phosphatase activity was expressed as total activity per rat lung (Fig. 16a). However, when expressed as units of activity per gram wet tissue, only a slight rise in concentration above the normal values was found (Fig. 16b).

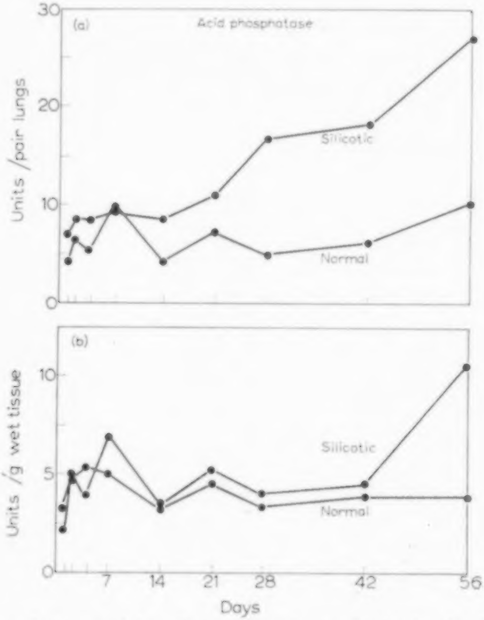

FIG. 16. Lung acid phosphatase activity of normal and experimental animals after the injection of 25 mg tridymite suspension.
(a) Values are expressed as total units of activity per rat lung.
(b) As units of activity per gram wet weight of lung tissue.

At about the fourteenth day period, the peripheral zone of the nodules became more intensely coloured than the central parts. In the later stages, this tendency became more pronounced and finally the collagenous central core of the nodule was completely depleted of acid phosphatase activity. A sharp line of demarcation was observed between the central collagenous core of the nodule, which was practically free of acid phosphatase activity, and the peripheral cellular zone which showed high activity (Fig. 17).

Sulphatase

Normal distribution. In normal rat lung tissue the sulphatase activity was localized to the bronchial epithelium, lymphoid tissue, blood and blood vessels and

macrophages. The lung capillary network was also coloured slightly red but no areas of high activity could be demonstrated in normal lung tissue. Sites of high sulphatase activity were stained blue-purple in sections of pathological silicotic lung tissue.

During the early period, 1–4 days, a slight increase in the intensity of background colouring was noted. This was apparently due to a general increase in the concentration of sulphatase during this period of cell infiltration. Foci in some cellular accumulations were coloured slightly blue, which indicated the formation of areas of higher sulphatase activity. These sites appeared to be mainly macrophage concentrations.

At 7 days the distinctive feature was the evolution of areas with high sulphatase activity, localized to macrophage concentrations in the central, intermediate and peripheral zones of the dust cellular concentrations (Fig. 18). The topographical distribution of some of these areas of high activity was confusing. These areas were not confined to dust cellular concentrations only but were also found in quite normal lung areas. Apparently this is due to dust-laden macrophage plugs in lymph vessels.

The 14 day period was characterized by a diffuse distribution of high sulphatase areas throughout the lung tissue and silicotic nodules. A greater tendency, however, was observed for these high activity areas to be now localized in and around the silicotic lesions.

From 21 days, a relative decrease in sulphatase activity apparently occurred in the well-defined collagenous nodules. Low sulphatase activity was demonstrable in the central collagenous part of the nodule, while areas of high sulphatase activity persisted in the peripheral zones until the termination of the experiment (Fig. 19). The chemical findings of the sulphatase concentration in developing silicosis are given in Fig. 20. In (A) the activity was calculated as total activity per rat lung while in (B) it was expressed as units of activity per gram wet tissue.

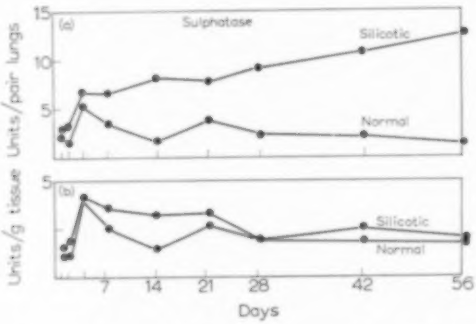

FIG. 20. Lung sulphatase activity of normal and experimental animals injected with 25 mg tridymite suspension.
(a) Values are expressed as total units of activity per rat lung.
(b) As total units per gram wet weight of lung tissue.

The relationship between the pathology and enzyme activity (*see Table* 1)

One and two day period. This period was characterized by cellular infiltration and concentration in the areas where the dust suspension was deposited in the lung tissue and was accompanied by general oedema and exudation of proteninous material. The alkaline phosphatase activity was very slightly increased in this period. The esterase

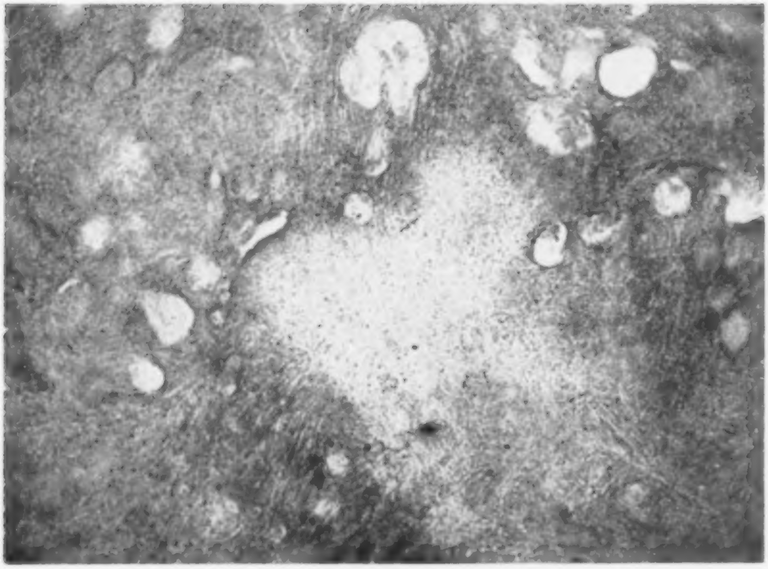

FIG. 17. Frozen section of rat lung, 28 days after injection of 25 mg tridymite. Low acid phosphatase activity in central collagenous part but high activity in peripheral zone of the silicotic nodule. ×90.

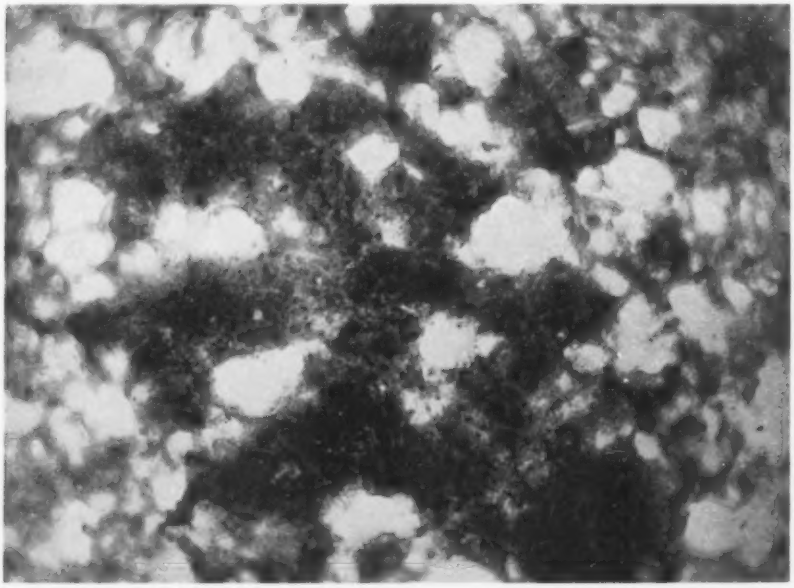

FIG. 18. Frozen section of rat lung, 7 days after injection of 25 mg tridymite. Areas of high sulphatase activity in silicotic lung. ×90.

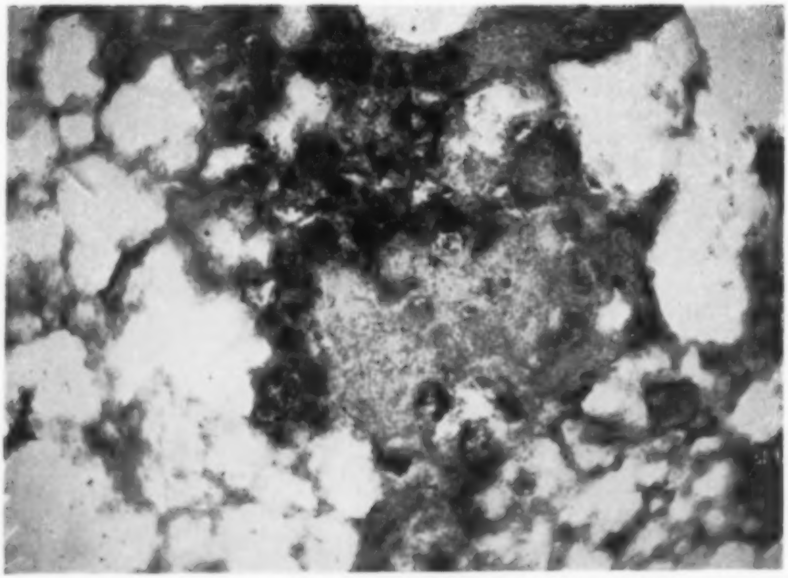

Fig. 19. Frozen section of rat lung, 21 days after injection of 25 mg tridymite. Areas of high sulphatase activity localized to tissue around silicotic nodule.

TABLE 1. SUMMARY OF ENZYME RESULTS

	Histological	Chemical (Total enzymes in lungs)
Alkaline phosphatase	Most marked in inflammatory stage (4 days), gradual return to normal.	Big early (4 days) increase; thereafter gradual increase.
Acid phosphatase	Marked increase from 7 days on; high concentration in cellular collections of dust. Later disappeared from collagenous areas; persisted in periphery. Very low activity in normals.	Steady increase throughout.
Sulphatase	Big increase from 7 days until end in collections of macrophages, beginning with reticulin formation. Low activity in collagenous parts, but enzyme persisted in, or in association with, the macrophages. Very low activity in normals.	Same as acid phosphatase, i.e. steady increase throughout, but not so marked.
Esterase	Marked increases in early stages up to 4 days, returning gradually to normal. No enzyme in collagenous areas; present in cells, particularly epithelial cells of vessels and bronchioles. In normals, very high activity in epithelium of bronchioles; walls of vessels and septal cells of alveolar walls.	Extremely variable from animal to animal, but marked increases in silicotics.

activity increased in proportion to the increase of polymorphonuclear cells, while no definite increase in either acid phosphatase or sulphatase activity was observed.

Four day period. The acute inflammatory stage was accompanied by degenerative changes in polymorphonuclear cells and necrosis and autolysis of the central parts of the compact cellular concentrations. No increase of reticulin fibrils was demonstrable at this stage, but apparently the normal reticular structure was slightly damaged.

This period was marked by a characteristic increase in alkaline phosphatase activity in the peripheral zone with only slight diffuse activity in the central necrotic areas of the cellular nodules. A marked reduction of non-specific esterase activity in the central necrotic parts of the cell concentrations was observed. In the peripheral zones, a high esterase activity persisted. In both acid phosphatase and sulphatase, a steady increase in activity occurred, and enzyme activity was in both cases localized to the cellular nodules. Areas of high sulphatase activity were just demonstrable.

Seven day period. This period was characterized by the infiltration of the central necrotic areas of the cell concentrations by fibroblasts and the formation of extra reticulin fibrils in these lung areas. In the peripheral zones of the nodules all kinds of cells were concentrated, i.e. polymorphonuclear cells, fibroblasts, histiocytes and macrophages.

As far as the enzyme activity was concerned, a relative decrease of alkaline

phosphatase in the peripheral zones with slight concentration in the central parts of the nodules was found. Esterase activity disappeared altogether from the central part of the nodules where reticulin formation was in progress, but the polymorphonuclear cells in the peripheral zone still showed high esterase activity. The acid phosphatase activity was very pronounced at this stage, and the nodular lesions were coloured bright red except in some foci in the centre, where collagen deposition was in progress. The sulphatase activity was now localized in areas of high activity, associated with histiocyte and macrophage concentrations within the nodules, and also scattered throughout the lung tissue, but was more abundant in the periphery of the nodules.

Fourteen day period. At this stage most nodules consisted of a compact nucleus of collagen, practically acellular and a peripheral zone with all kinds of cells. The distribution of alkaline phosphatase activity was quite normal except that some newly-formed arterial walls in the peripheral zone were coloured black. The esterase activity remained the same as in the previous period. The acid phosphatase showed a tendency to be more strongly localized in the peripheral zone than in the central collagenous core. Areas of high sulphatase activity were localized in the peripheral zone and persisted here until the termination of the experiment. The central collagenous core showed only moderate sulphatase activity.

No further changes in the localization of the different enzymes investigated were observed.

DISCUSSION

In this investigation an attempt was made to describe the early histology of the silicotic nodule in rat lung tissue and to correlate the pathology with enzyme activity during fibrogenesis. No evidence could be adduced from the *in vivo* experiments to support the idea of adsorption of enzymes on the particle surfaces, although several authors have demonstrated the adsorption of different enzymes and complex substances *in vitro* on quartz surfaces (DALE and KING, 1953; SCHEEL *et al.*, 1954; HOLT and BOWCOTT, 1954; LUHNING, 1954). It was also not possible to demonstrate adsorption of inhibitors (cf. BAUMANN, 1955) with the experimental procedures used.

The chemical determinations of the enzyme concentrations in silicotic tissue were not entirely satisfactory. The esterase method was found to be unreliable in our hands and we do not feel that the results give a true picture of the esterase activity. A correlation for the other enzymes between the chemical findings and histochemical data could be demonstrated when the enzyme concentration was expressed as units of activity per gram wet weight of lung tissue. This is particularly true in the case of alkaline and acid phosphatase. The total activity per rat lung, however, was higher after the injection of the tridymite suspension. This was due to the increase in weight, with time, of the lungs of the experimental animals. If the weight increase of the lung is regarded as an indication of collagen deposition, then there appeared to be a correlation between collagen formation and the elevation in the alkaline and acid phosphatase and sulphatase concentration.

The sharp increase of the alkaline phosphatase activity in the acute inflammatory phase may be of importance as a trigger mechanism in fibrogenesis. At this stage the disintegration of polymorphonuclear cells was abundant, with the result that much proteolytic enzyme was set free. These enzymes played some rôle in the liquefaction and resolution of the proteinous exudate of the earlier stages. Not only destruction

of cellular elements occurred, but also the normal reticular structure was damaged where the particulate material was deposited. The liquefaction of protein material and the proliferation of extra reticular fibres were two events going hand in hand. The evolution of extra reticulin fibres started about the fourth day, and at this period the alkaline phosphatase activity was relatively high while there was a decline in esterase activity. From the histological appearance of the central part of the silicotic lesion at this stage, it was evident that only the fibrocytes and histiocytes survived the acute toxic effect of the tridymite particles. These fibrocytes in their new abnormal environment, are believed to play a major part in the evolution of extra reticular fibrils.

The relative increase in alkaline phosphatase activity may be associated with an uncoupling of the oxidative phosphorylation process in the mitochondria of cells in the silicotic cellular concentrations. DIANZANI and SCURO (1956) claimed that substances like histological dyes produced activation of ADP, nucleotidase, and both alkaline and acid phosphatase of liver *in vivo*. It is known that colloidal silica behaves like histological dyes in enzyme systems and perhaps interferes with oxidative phosphorylation. Experimental evidence is altogether lacking, but it is suggested that organic and inorganic phosphate estimations on control and silicotic tissues might be worth doing.

In this investigation both the acid phosphatase and sulphatase activity increased in the cellular nodules following the acute inflammatory stage. This activity lasted until the collagen reached a certain grade of maturity and then disappeared from the collagen core, but remained localized in the outer zone where collagen deposition was still in progress. The topographical distribution and localization of sulphatase activity in silicotic lung tissue is difficult to link with collagen deposition. Areas of high sulphatase activity were associated with macrophage concentration and areas of haemorrhage. Low activity areas were diffusely distributed throughout the whole of the silicotic nodule except in the very early stages. There is perhaps a relationship between sulphatase activity in the silicotic lung and the conversion of ground substance (chondroitin sulphate) to collagen.

The net impression from the work described here is that the enzyme changes result from the ebb and flow of the different cells populations. They may be concerned in the series of changes which lead to fibrous tissue formation, but they are only part of the biological response to injury by quartz. This is primarily, at least in its early stages, a cellular response, and the alterations in enzyme concentrations only reflect the cellular changes.

SUMMARY

(1) The distribution and localization of alkaline and acid phosphatase, non-specific esterase and sulphatase in silicotic lung tissue have been investigated histochemically and chemically.

(2) A survey of the early histology of the pathogenesis of the silicotic nodule is presented and the cytobiological responses are correlated with changes in enzyme activity.

(3) Alkaline phosphatase and non-specific esterase may be involved as a starter mechanism in the fibrogenesis of reticular tissue, while it is also suggested that acid phosphatase and sulphatase may have some connexion with collagen disposition.

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THE PNEUMOCONIOSIS FIELD RESEARCH OF THE NATIONAL COAL BOARD

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INTRODUCTION

THE problem of pneumoconiosis among coalminers in this country is by no means a new one (MEIKLEJOHN, 1952), but it is only in the last 25 years or so that some indication of its extent and severity has been available. Even this knowledge is largely limited to information about particular areas (COCHRANE *et al.*, 1956; MCCALLUM and BROWNE, 1955) and to a record of the numbers of men newly certified each year as suffering disability.

Approximately 30,000 cases were diagnosed in Great Britain during the years 1931 to 1949, more than three-quarters of them being in South Wales. Since 1949 there has been a decrease in the annual certifications in the South Western Division of the National Coal Board (i.e. essentially South Wales), from 4371 in 1949 to 703 in 1957. On the other hand, in the other eight Divisions of the Board the numbers have risen from 1436 in 1949 to 3053 in 1957. The total number of new certifications in 1957 was therefore 3756, compared with 5807 in 1949.

The value of this information is, of course, limited by two considerations. First, the men now coming forward for certification are exhibiting a condition attributable to the environment which they have experienced over many years. Secondly, the extent to which they have voluntarily presented themselves for examination has depended upon a number of factors, including their awareness of the disease and economic considerations. It is therefore not possible either to estimate the true prevalence of pneumoconiosis or to assess it in terms of present environmental conditions. Nevertheless, the information available shows that pneumoconiosis is still an extensive problem in coalmining, and that it is not confined to South Wales.

This represents a considerable change in opinion over the last 20 years. During the 1930's it was thought that pneumoconiosis was almost entirely limited to South Wales, particularly the anthracite area, where the inhalation of anthracite dust was considered to be by far the most important factor. For this reason, the investigation which was undertaken by the Medical Research Council in the years 1937 to 1942 was conducted at 16 collieries in South Wales. This survey, reported in a series of Medical Research Council Special Reports (Medical Research Council, 1942, 1943, 1945), was an attempt to correlate the prevalence of pneumoconiosis with the past environmental histories of the men examined, particularly in terms of the dust concentrations to which they had been exposed. As a result of this work, the present "approved" levels of dustiness for British coal mines were adopted (National Coal Board, 1948).

There were several other practical and important consequences of the Medical Research Council investigation. These included a change in 1943 in the law relating

to certification (Workmen's Compensation Act, 1943; Coal Mining Industry (Pneumoconiosis) Compensation Scheme, 1943), whereby the scope of eligibility for compensation was extended, and the very high certification rates in South Wales for the next few years were undoubtedly a direct result of this change. Another outcome of the investigation, supported by the recommendations of a committee appointed in 1943 by the Minister of Fuel and Power (Ministry of Fuel and Power, 1944), was the establishment in 1945 of the Pneumoconiosis Research Unit (P.R.U.) of the Medical Research Council at Cardiff.

A further logical development was the decision taken in 1947, jointly by the National Coal Board, the National Union of Mineworkers, the interested Ministries and the Medical Research Council, that men suffering from simple pneumoconiosis would no longer be precluded from working in the industry, but would be placed as far as possible in work "in approved dust conditions" (National Coal Board, 1948), and subject to periodical medical examination. This was a purposeful and imaginative decision by all the parties concerned. It recognized, or rather implied, (i) that simple pneumoconiosis would not progress if the dust concentrations were below certain levels; (ii) that these levels could be specified in terms of numbers of particles of dust, within a certain size range, per unit volume of air; these approved levels of dustiness were based on a commonsense interpretation of the environmental data accumulated in the Medical Research Council survey, coupled with a consideration of what could be achieved in practice, using efficient dust suppression methods; and (iii) that as simple pneumoconiosis was not necessarily associated with serious disability, men with this condition should not automatically be excluded from continuing to work underground.

By 1952 the workers at the Pneumoconiosis Research Unit at Cardiff had made detailed studies of the clinical, pathological, epidemiological and radiographic aspects of the condition (FLETCHER, 1948; STEWART *et al.*, 1948; FLETCHER *et al.*, 1949; GILSON and HUGH JONES, 1949; FLETCHER and OLDHAM, 1951; COCHRANE *et al.*, 1951; COCHRANE *et al.*, 1952). They had put forward the "two-disease hypothesis", which divided coalworkers' pneumoconiosis into simple pneumoconiosis and complicated pneumoconiosis (or progressive massive fibrosis). Simple pneumoconiosis was considered to be caused by dust alone, and complicated pneumoconiosis by the addition of an infection, probably tuberculous, on lungs already affected by coal dust. Important differences in the pathology, radiographic appearances and prognosis of the two types had been described.

Even so, there were many uncertainties in regard to, (*a*) the true prevalence of pneumoconiosis throughout the country; (*b*) the attack and progression rates of the disease under various conditions; (*c*) the establishment of a satisfactorily "safe" environment in terms of both quantity and quality of dust; and (*d*) the relationship between the disease and respiratory disability. Accordingly, the National Coal Board were pleased to accept an invitation by the National Joint Pneumoconiosis Committee in 1952, to "undertake a field research in order to determine how much and what kinds of dust cause pneumoconiosis and to establish what environmental conditions should be maintained if mine workers are not to be disabled by the dust that they breathe during the course of their work". This research was to be a long-term survey over a period of at least 10 years at a representative sample of collieries. With these objects in mind the Pneumoconiosis Field Research was started by the Board in 1952 (FAY, 1957).

THE SELECTION OF THE COLLIERIES

The selection of collieries was obviously not to be confined to South Wales, because for one reason pneumoconiosis was manifestly present throughout the British coalfields. Even more important, there was no evidence to show that airborne dusts in coal mines in all parts of the kingdom are of equal toxicity, and information on this aspect was essential to establish whether or not all collieries should be subject to the same levels of "permissible" dustiness. Accordingly, account was taken of four factors which were thought most likely to have an effect upon the problem. These were: (i) level of dustiness, (ii) rank of coal mined, (iii) presence of quartz in the strata associated with the coal seam, and (iv) ash content of coal seam *in situ*. These factors encompass, directly and indirectly, the main features of quantity and nature of dust encountered in British coal mines. The four factors were considered at two levels, "high" and "low", giving a statistical design for the experiment consisting of sixteen "boxes". The collieries were selected on the basis of this design, in such a way as to fill each of the boxes. In order to make the selection representative of all the coalfields, it was necessary to increase the number above sixteen, and altogether twenty-five collieries were finally chosen. Certain obviously desirable features, such as reasonable size and a predicted life (without major change) of at least ten years, were borne in mind. In the event, five collieries were chosen in Scotland, two in Northumberland, one in Cumberland, two in Durham, three in Yorkshire, one in Lancashire, one in North Wales, one in Nottinghamshire, one in North Staffordshire, one in Warwickshire, six in South Wales and one in Kent. The total number of men under observation at these twenty-five collieries is about 35,000, some 5 per cent of the total mining population in this country.

It is unlikely that the formal factorial design will play a very big part in the final statistical analysis of the results, since it is intended to take account in greater detail of the various factors relating to quantity and quality of the dust. The present selection is, however, considered to represent a balanced sample, giving a reasonable cross-section of mining practices and conditions in England, Scotland and Wales. Indeed, one interesting finding which has already emerged is that the prevalence of pneumoconiosis is exceptionally low in some areas.

THE PLANNING OF THE RESEARCH

Once the collieries had been selected, the planning of the investigation fell into three clear divisions: (*a*) the medical studies, (*b*) the environmental studies and (*c*) the assembly and analysis of both sets of data, including the necessary medical/environmental correlations.

THE MEDICAL STUDIES

The primary objects of the medical surveys are to establish the prevalence of pneumoconiosis and to study the changes in the chest condition of the men with time. An incidental aspect of the surveys, but nevertheless one of great importance, is that each man examined is notified of the findings in his own case.

To carry out the surveys two mobile X-ray Units are employed, each under the supervision of a Medical Officer. One unit is based at Edinburgh and one at Cardiff, each covering about a dozen collieries in the north and south respectively.

A chest X-ray is taken of every member of the population at each colliery who comes forward for examination. Full-size chest X-ray films are used (Fletcher, 1952), and

the technique adopted is that recommended in the Ministry of Health Memorandum on Standardisation of Technique in Chest Radiography (Ministry of Health, 1952).

Very great efforts are made to achieve standardization of radiographic technique so that the X-rays taken on any given survey and on future surveys shall be comparable. An exposure control device is incorporated in the equipment and, in order to minimize variations due to processing, an automatic unit is used with careful control of developer temperature and activity (Clarke, 1953; Stamford and Hills, 1956).

The films are categorized according to the I.L.O. classification (I.L.O., 1953), which distinguishes the two types of pneumoconiosis—simple pneumoconiosis, divided into Categories 0, 1, 2 and 3, and complicated pneumoconiosis, or progressive massive fibrosis (P.M.F.), divided into Categories A, B, C and D. Standard films supplied by the Pneumoconiosis Research Unit are used to assist in the classification of the films (Fletcher and Oldham, 1951).

Before the start of a survey the aims of the research are explained to the men, to their family doctors, and to the doctors of the local chest clinics and of the Pneumoconiosis Medical Panels of the Ministry of Pensions and National Insurance.

The X-ray findings are confidential to the Unit Medical Officer, with whom the man, who is informed of them by letter, may discuss them subsequently if he wishes. The advice given to each individual is based on the X-ray picture, his age and occupation. Where the appearances of the film are suggestive of pneumoconiosis, the man is advised to apply to the appropriate Pneumoconiosis Medical Panel for compensation, and in these cases the film is made available to the Panel. Where another abnormality is suspected, the man's permission is sought to pass on the information to his family doctor, who arranges such further action as may be necessary.

The population of the selected collieries will be X-rayed regularly every four years or so. The first medical survey has now been completed at each colliery, the overall response being 94·8 per cent. Thus, information is available as to the present radiological classification of more than 30,000 men. The follow-up surveys will provide a record of the radiological changes (if any) amongst these men, or at least those of them who are examined on successive occasions.

It is realized that the radiological classification is not necessarily related to the extent of the disability (if any) suffered by a man (Gilson *et al.*, 1955), and further information is required in this field. For this reason, physiological tests of respiratory function and a questionnaire of respiratory symptoms have been introduced in the second round of medical surveys, and for this purpose a Physiologist has been appointed to the staff of each Medical Unit. The object of this work is to investigate the relationship between X-ray category and disability, and so to add to existing knowledge of the clinical importance of the disease.

THE ENVIRONMENTAL STUDIES

The environmental studies are required to establish as accurately as possible the environment of all the men under observation, with the object of correlating each man's successive X-ray classifications with his intervening environmental exposure.

The concentrations of "respirable" (1–5 micron) dust are made using the Thermal Precipitator as the standard sampling instrument. Since the object is to measure the actual dust concentrations encountered, and not to assess maximum concentrations for control purposes, the procedure is to sample the environment in the vicinity of the

man under observation and not the general environment. This is an extension of the "Random Collier" method suggested by OLDHAM and ROACH (1952), who advocated pooling all the colliers at any one pit and randomly selecting representatives whose environment would be measured throughout a shift. The "Random Collier" procedure was modified for three reasons. First, information was required about all the other occupations as well as that of collier. Secondly, it was felt that considerable variations must exist between the environments of different colliers, even in the one pit, and this information would be lost by pooling the men for sampling purposes. Thirdly, it was thought preferable to start by accumulating information in as much detail as possible; the detailed information could always be summarized, whereas by starting with only a comparatively coarse stratification there would be no opportunity of breaking down the results on a more detailed basis should this later prove to be necessary.

Ideally, each man should have a record of his measured environment, day in and day out, to match his medical history on an individual basis. With 35,000 men under observation, this is manifestly impossible, so that some form of sampling procedure is essential. The method adopted is to stratify the population at each colliery into "occupational groups", consisting of men doing the same job, at the same place, at the same time. The first division is in terms of faceworkers, non-faceworkers underground and surface workers, further sub-divisions being by place of work (e.g. individual coalface), occupation (e.g. collier, ripper) and shift. In this way the population under observation is divided into reasonably small and homogeneous occupational groups, in any one of which the environment can be expected (and subsequently checked) to be uniform. At any one time there are approximately 1500 such occupational groups under current observation at the twenty-five collieries.

The environment of these occupational groups is measured by randomly selecting representatives by name, and having their environment measured throughout a shift. The sampling fractions for the first environmental surveys were fixed arbitrarily at about one shift sampled for every ten members of the group, and an "occupational group exposure index" was built up by averaging the results obtained from each contributory shift of sampling. The application of an arbitrary sampling fraction in the initial stages was unavoidable, because of the lack of knowledge of dust concentrations. With the information and experience which have subsequently been obtained, the allocation of sampling effort is now based on a formal statistical procedure, which takes account of the time for which the group remains in being, the standard deviation of the individual shift results and the number of men belonging to the group (ASHFORD, 1958a).

The composition of the groups, as well as the current groups themselves, are naturally subject to frequent change, not only because of working places (especially coalfaces) closing down and being replaced by others, but also because some of the men frequently change their places of work, occupations or shifts. It is therefore essential to keep an accurate record of the working history of each of the 35,000 men, and this is done on an individual record card. By so doing, it is possible to apply the appropriate "occupational group exposure index" to each man for the period during which he was a member of the group, and in this way an "individual exposure index" is cumulatively built up on his record card. The group exposure index is

recorded in terms of the product of mean dust concentration and length of shift, and the individual exposure index is obtained by multiplying this product by time at risk (i.e. number of shifts worked in the incremental period, due allowance being made for absence and overtime).

Investigators based at each colliery sample the environment of randomly selected representatives according to a formal and strict programme, based upon the distribution of the pit population at the time of the survey. Dust concentrations are measured and a number of other observations including effective temperature are also made. The programmes are designed to complete a survey of the entire pit population in about 6 months. This is desirable in order to allow for changes in working places, mining practices and so forth, which are entirely outside the control of the investigation.

The procedure for measuring dust concentrations is to take samples with the thermal precipitator as near the man as possible and in such a way as to be representative of the air he breathes. The duration of each individual sample is adjusted according to the estimated concentration of dust present, in order to obtain samples suitable for accurate evaluation. As soon as one sample is stopped another is started, so that a record is obtained of the variation of dust concentrations throughout the shift. At present, these results are averaged, after due weighting for sampling time, but the individual results are recorded as evidence of the existence or otherwise of high "peak" concentrations within the shift. The samples are evaluated by the investigators themselves, using projection microscopes.

Up to the present, the emphasis in dust sampling has been mainly on the quantitative estimation of dust concentrations in terms of numbers of particles in the size range 1–5 microns, and this has been so for two reasons. First, it was essential to establish an adequate background of information on dust concentrations as early as possible, in order to place the sampling procedures on a firm and logical basis. Secondly, the experiment has to be designed with the object of testing a specific hypothesis, and it seems reasonable to test the simplest hypothesis first—namely, that radiological pneumoconiosis of coal miners is related to the total quantity of dust breathed. At the same time, the qualitative aspect has not been neglected, lest it prove necessary as a second step to investigate the effect of composition of the dust. For this purpose, the percentage of non-coal particles in each sample is estimated by visual assessment of the thermal precipitator slides. In addition, a start has been made on the collection of samples of respirable dust in sufficient quantity for compositional analysis, using the "Hexhlet" sampler (WRIGHT, 1954). Only a few Hexhlet samples have so far been collected, but the results suggest that the method of visual discrimination of coal and non-coal routinely employed in the evaluation of the thermal precipitator slides is reasonably accurate (FAY, unpublished).

Another safeguard which has been adopted is to evaluate the dust samples in terms of the $0{\cdot}5$–5μ particle concentrations, as well as in the 1–5μ range, in case it should prove necessary later to investigate the effect of the smaller particles. In addition, there is, of course, the accumulation of all the information about individual thermal precipitator samples, for use should the need arise to investigate the effect of "peak" concentrations.

The measurement of dust concentrations is a fundamental requirement in assessing the environmental hazard, but the information collected is not necessarily the best

measure which can be applied. For example, it is likely that the amounts of dust which the men breathe and retain in their lungs will depend upon the strenuousness of their work, and it may be necessary to study the relative breathing rates associated with different occupations, so that appropriate factors can be applied.

THE MEDICAL/ENVIRONMENTAL CORRELATIONS

One of the main purposes of the research is to investigate the relationship between progression of radiological pneumoconiosis and dust exposure, and the building up of the medical and environmental records on an individual basis for all the men under observation is designed with that object in view. As soon as a sufficient number of men show signs of progression, quantitative correlations between dust exposure and disease will be attempted, but with the present efforts by the Board to reduce dust concentrations to progressively lower levels, it may be some years before any significant progression, even in the early categories of simple pneumoconiosis, will be manifest.

For this reason, an attempt is being made to extract as much useful information as possible from the data already collected. At the time of the first X-ray a full working history was recorded for each man examined, showing in detail his places of work and the occupations he had followed since leaving school. In this way a record is available, for each man, of his present X-ray category and his past occupational history. The histories are coded and summarized on an electronic computer for subsequent analysis on Hollerith equipment. The first step is to select as many men as possible with a reasonably "pure" environmental history, in the sense of having worked primarily at the colliery at which they were examined, and for the bulk of their working life in one occupation. By this means it is possible to extract a number of men in various "pure" exposure categories ("pure collier", "pure ripper", and so on) at each colliery. Their radiological categories at the time of the X-ray are then analysed in terms of years of exposure in the various "pure" exposure categories, from which, by biological assay methods, it is possible to prepare dosage/response curves and hence to deduce such parameters as the E.D. 50s for, say, category 1 pneumoconiosis (i.e. the number of years of exposure in the occupation in question which has resulted in 50 per cent of the men so exposed and examined reaching category 1 pneumoconiosis). No attempt has been made to interpret these results in terms of dust exposures, as insufficient information is available about dust concentrations in the past to enable any quantitative relationships to be deduced. Nevertheless, provided sufficient numbers of men are available, these parameters are a useful basis of comparison of the relative past hazards associated with different collieries and different occupations.

Unfortunately, sufficient numbers are not available at all the collieries, and in all the occupations of interest, to enable very extensive comparisons to be made in terms of the "pure" exposure categories. The analysis has therefore been extended to cover all the men examined in terms of more general past environments—coalface (coalgetting shift), coalface (non-coalgetting shift) and non-facework underground. A "multi-dimensional" method of analysis has been applied in this part of the work, whereby the relative hazard associated with each type of environment can be assessed. In this way, more useful comparisons can be made between the past hazards at different collieries and in different occupations.

PROGRESS TO DATE

Medical surveys

The first medical surveys have been completed at all twenty-five collieries, with an overall response of 94·8 per cent. The prevalence of pneumoconiosis varies from very little significant pneumoconiosis at some collieries (1 per cent of Category 2 or more) to a considerable amount at others (about 20 per cent of Category 2 or more).

The second round of surveys has started and, in addition to the X-ray examination and the compilation of details of environmental exposure, certain anthropometric indices and the results of respiratory function tests are now recorded for each individual. A questionnaire seeking to establish the presence and duration of symptoms of respiratory disease is also used.

Environmental surveys

At least four complete environmental surveys of the whole population have been made at each of the twenty-five collieries, and further surveys are well advanced at most of them. The more formal allocation of sampling effort will ensure that progress at all the collieries will in future be more regular than it was in the past.

In all, more than 14,000 shifts have been sampled, involving the collection and evaluation of about 60,000 thermal precipitator samples. Two satisfactory features have emerged from the results. First, the refined stratification adopted has been shown to have been justified, in that considerable differences in dust concentrations have been measured between similar occupations, e.g. colliers working on different faces at the same colliery. Where the results justify it, groups with similar environments are pooled for subsequent surveys, and conversely groups are further subdivided if the measurements indicate that this is desirable. On the whole, however, relatively little pooling or further subdivision has proved necessary. Secondly, the measurements made during the second and subsequent surveys at each colliery have in general confirmed those of the first survey, and the confidence intervals associated with the results have progressively narrowed. As with the prevalence of pneumoconiosis revealed by the X-ray surveys, a wide range of dust concentrations has been found. For example, the average concentrations on the coalface, coal-getting shift, vary from 100 to about 700 p.p.c.c. (1–5μ) at the different collieries.

Medical/environmental correlations

The analysis of the past working histories of the men examined on the first medical surveys is nearly completed, and the "definite" X-ray readings are available. The data for nearly all the collieries have been fully analysed, including the calculation of E.D. 50s and E.D. 20s for different groups of the populations, and the analysis of the results obtained at the last few collieries is well in hand.

The analysis includes an examination of the data relating to the "lapses", i.e. the men who did not come forward for X-ray examination, and it appears that these do not represent a significant proportion with respect to either age or employment. It is therefore concluded that the relationships found can be applied to the present pit populations as a whole.

MAINTENANCE OF ACCURACY AND CONSISTENCY

In a long-term research of this type it is obviously essential to maintain a rigid control over the procedures of measurement and the recording of the information

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collected. In some respects the data are self-checking, as, for example, in the consistency of the results obtained in the environmental measurements, but in other respects a deliberate effort has to be applied to assess the confidence which can be placed in the data reported at any stage of the investigation. One feature which stems from this requirement is the need to document progress and developments promptly at all stages. For example, as each environmental survey at each colliery is completed, the results are summarized to record not only the results from that particular survey, but also the cumulative results obtained from that survey and the previous ones. Similarly, changes in techniques and procedures are formally reported, as well as progress in the various aspects of the research. Some of these developments are described briefly below.

X-ray readings

The observer error in classifying films by X-ray category is by no means negligible (FLETCHER and OLDHAM, 1951) and every effort is made to make the final (or "definitive") readings as accurate as possible, and to estimate their probable accuracy.

The procedure for classifying the films is for each Unit Medical Officer to read the films taken by his unit in the field at the time of the survey. These results are reported as provisional figures and any necessary action in the field is taken on the basis of these readings. The films are then read independently by the other Unit Medical Officer, so that all the films from every colliery are read at least once by each observer independently. On those films for which the independent readings are the same, the common reading is taken as the "definitive" classification. Films for which the independent readings differ are re-examined by the two Medical Officers in consultation, and they assign the definitive reading on the basis of their joint discussion.

All the readings made by the Medical Officers are analysed for intra-observer and inter-observer consistency. By a development which will be described later, the performance of the readers is kept constantly under review, and it is possible to estimate the accuracy of the definitive readings which they report.

Experiments have also been made by the Medical Officers to investigate the X-ray techniques with the object of further standardization of procedure. This work is directed towards the elimination of certain variations in the quality of the films which have been evident during the first surveys.

Environmental sampling and assessment

The technique for sampling the environment has already been described. The object is to take samples which are representative of the air breathed by the man under observation. As far as possible formal procedures are laid down, but the working conditions underground are such that the investigator frequently has to use his discretion as to where he should locate the thermal precipitator. To check that the normal sampling procedures are reasonably accurate a series of experiments was carried out, in which the results obtained by the routine methods were compared with those obtained when the sampling instrument was (with no little inconvenience to the subject) worn in a harness on the man's chest. No significant differences were found, and it is considered that the routine procedures give the necessary accuracy (GRAHAM, unpublished). Similarly, any variations in sampling practices (e.g. the use of the thermal precipitator with its sampling head inverted, in places where water dropping from the

roof otherwise renders the samples useless) are subjected to a careful check before they are put into use (HADDEN, unpublished).

The counting of the thermal precipitator slides is, of course, a source of possible inaccuracy, and a close and continuous check is kept on the performance of the investigators in this respect. In the early days of the research a number of instruction courses were held, at which the investigators were trained to count to a uniform standard and their counting levels stabilized. New members of the team, immediately on appointment, are sent on instruction courses, and further courses are held as and when the control procedure indicates the need. The development of a new and improved method for maintaining a continuous check on counting levels is described later.

THE DEVELOPMENT OF NEW PROCEDURES

Particular care was taken over the long-term requirements during the planning of the research, and the temptation to introduce changes without due forethought has been avoided. Nevertheless, a number of desirable extensions and developments have been introduced, as was inevitable in view of the fact that much of the early planning was necessarily empirical. In particular, the methods of treating the data have been kept continuously under review, and new techniques have been developed to improve the handling, analysis and utilization of the large and complicated mass of information collected in the field.

Mathematical model for the analysis of X-ray readings

A new mathematical model has been developed for the study of observer error associated with the radiological classification of pneumoconiosis (ASHFORD, unpublished). This model is based on an examination of the results obtained in the first X-ray surveys, and provides an estimate for the probability of a single reading, selected at random, being correct. Hence an estimate of the probability of a correct "definitive" classification being assigned to a film is deduced. The model has been applied to the readings obtained and it has been shown that the levels of categorization of the X-rays have remained steady, and that a satisfactory degree of consistency has been achieved by the readers. Various alternative methods of arriving at the definitive reading have been examined by this model.

Thermal precipitator counting check

The consistency of the investigators in evaluating their samples has been subject to check throughout. In the early days the procedure involved the circulation of a number of test slides according to a statistical design, followed by an analysis of the results, taking the team of investigators as a whole. This was found to be a lengthy procedure, and the results became available too late to have any immediate effect upon the performance of the participants. A new procedure was therefore devised, based upon a pyramid hierarcy with four "Master Counters", each selected from one of four regions of the country. The mean level of these Master Counters is taken as the reference standard for the whole team. In the next step, each Master Counter is associated with three other Senior Investigators in his region, and each Senior Investigator in turn with the Junior Investigators under his jurisdiction. Reference slides are counted every month by each group, and a "league table" of counting levels is circu-

lated monthly. Refresher courses are arranged, as necessary, and a regular check is thus maintained on the performance of all the members of the team (FAY and SMITH, unpublished).

Multi-dimensional analysis of the past environmental histories

The analysis of prevalence in terms of past working history were originally performed using standard methods of probit, and later logit, analysis. A limitation soon became evident, due to the low prevalence of pneumoconiosis and the small numbers of men with "pure" histories, at some of the collieries. A better method of analysis was therefore developed, based upon a "multi-dimensional" approach, in which different types of environment are considered as separate dimensions in the history of past exposure (ASHFORD, 1958b). The extensive computations involved are carried out on an electronic computor.

The maintenance of manpower records

In view of the frequent changes in occupation and place of work which many of the men under observation undergo, the compilation of an accurate environmental record for each man is difficult, but essential. At the beginning, the procedure was to revise the manpower distribution list at each colliery on a quarterly basis, without taking into account any changes within the three-month period. The method was later refined by having a weekly record kept for each man. These individual record cards are maintained in the colliery offices and cover a 13-week period. Even so, the clerical work, both at the colliery and at headquarters, is considerable and a new method has been developed, based on the use of "mark-sense" Hollerith cards at the colliery. These cards, one for each man employed at the colliery, are sent to headquarters every week, where they are processed on Hollerith and the records produced entirely mechanically. In this way an individual record is maintained, covering occupational group and time at risk (including absences and overtime) on a weekly basis, suitable for summarizing at any convenient interval. A revised manpower distribution list by name can also be printed automatically whenever it is required. This procedure is now in use at about half the collieries, and it is planned to extend its use to the other collieries as rapidly as possible.

ORGANIZATION

The investigation is undoubtedly one of the biggest ever undertaken in the field of occupational hygiene, and naturally a large number of people are involved. The research as a whole is under the direction of the Chief Medical Officer of the National Coal Board (Dr. J. M. ROGAN), who himself supervises the medical studies. The environmental studies, and the correlation of the medical and environmental data, are the responsibility of Mr. D. HICKS, then Director of Scientific Control, to whose staff one of us (J. W. J. F.) was appointed as Chief Scientist of the Research in March, 1953. The general progress of the work is guided and supported by a Steering Committee, which is a sub-committee of the National Joint Pneumoconiosis Committee. The present Chairman of the Steering Committee is Mr. A. H. A. WYNN, who succeeded Sir CHARLES ELLIS in 1955. The members of the Steering Committee include representatives of the Medical Research Council, the Ministry of Pensions and National Insurance, the Ministry of Power, the National Association of Colliery

Overmen, Deputies and Shotfirers, the National Coal Board and the National Union of Mineworkers.

On the medical side, each X-ray Unit has two Medical Officers, two Radiographers, three Clerks, one Driver/Darkroom Attendant and one Secretary. An Administrative Officer is employed in the Chief Medical Officer's office, giving a total staff of nineteen engaged on the purely medical aspects.

The environmental studies employ eighteen Scientists and thirty-nine Scientific Technical Officers in the field, amounting to a total staff of fifty-seven Investigators, an average of just over two per colliery. These Investigators are responsible to the Chief Scientist at headquarters.

The Headquarters Unit, under the Chief Scientist, contains six graduate Scientists, including four mathematical statisticians, and twelve Scientific Technical Officers (including Computers). These people are directly concerned with the preparation of the environmental sampling programmes, the analysis of the environmental results, the medical/environmental correlations, the manpower records and studies, the analysis of X-ray readings, the inter-Investigator counting checks, and, by no means least, the development of new methods and procedures. They also collaborate with the Medical Officers in the design of their experimental work and techniques. In addition, there are fifteen Clerical Officers and Clerks, a Secretary and seven administrative and typing staff, giving a total complement of forty-one in the Headquarters Unit.

Altogether, therefore, there are nineteen people engaged on the medical side, and ninety-eight on the environmental studies and the medical/environmental correlations, making a total of one hundred and seventeen employed full-time on the investigation.

CONCLUSION

The research is as yet only in its early stages and the ultimate objective of recommending "safe" levels of dust is still a long way off. Nevertheless, it is now apparent that the long-term planning was satisfactory, and that the experiment is running well, nothing having emerged to suggest that either the broad outline or the matters of detail would be planned on radically different lines if a fresh start had to be made.

The planning and growth of the research have, of course, provided an exceptional opportunity to study many interesting problems associated with the progress of the field work and the analysis of the data. Indeed, the development of new techniques and methods of analysis, to solve the problems which arise and to refine the available means of tackling them, has done much to mitigate the exacting but essential task of pursuing the routine measurements. Much of the work which is of general interest will be published in due course.

Acknowledgements—It has been our privilege to write this general account of the Pneumoconiosis Field Research of the National Coal Board, but it will be obvious that many people contribute individually and collectively. The programme would not be fulfilled without the enthusiasm of the doctors, scientists and technologists in the field and at headquarters, nor would the investigation be possible without the ready and enthusiastic co-operation of the men, the Managers and other officials at the collieries, and of the staff of the Board's Scientific Department and Medical Service at Divisions and Areas.

The individuals concerned are too numerous for us to mention them all by name, but we should like to express our especial gratitude to Dr. ROGAN and Mr. HICKS for their constant encouragement and advice.

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ÉTUDE DE LA GRANULOMÈTRIE DES BROUILLARDS PAR PHOTOGRAPHIE DIRECTE DES GOUTTES LIQUIDES EN SUSPENSION DANS L'AIR

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Sommaire

Au cours d'une première partie qui sert d'introduction, on rappelle brièvement les principes des méthodes granulomètriques actuellement utilisées pour caractériser les brouillards de gouttelettes, on expose les difficultés que présente la photographie directe des gouttes en suspension dans l'air, et on décrit un appareillage destiné spécialement à l'étude des liquides volatiles. Celui-ci consiste à photographier les gouttes entrainées par un courant d'air, qui passent dans le champ d'un microscope éclairé latéralement.

Au cours d'une seconde partie, on interprète l'aspect d'une gouttelette d'eau éclairée latéralement et examinée au microscope. On observe trois images différentes correspondant à la lumière réfléchie à la surface extérieure, transmise directement par la goutte, et transmise après deux réflexions internes. Calcul de l'éclairement de ces images en se basant sur les résultats théoriques de Wiener.

Enfin on explique l'aspect des images données par l'appareil proposé, on donne une idée de ses performances que l'on compare avec celles des méthodes habituelles d'observation.

Abstract

In an introductory section the methods of sizing clouds of droplets are outlined, the difficulties of direct photography of drops in air are pointed out, and an apparatus specially designed for the study of drops composed of volatile liquids is described. In this apparatus the drops are photographed as they are swept by a jet of air through the field of view of a microscope, the illumination being at right angles to both air movement and the axis of the microscope.

In the second part the appearance under the microscope of a water droplet illuminated laterally is interpreted: three parts of the image appear bright, one corresponding to light externally reflected by the drop, one to light directly transmitted and one to light transmitted after two internal reflexions. The brightness of these three images is calculated on the basis of Wiener's theoretical results.

Finally, the appearance of the images obtained with the proposed apparatus is explained, and its performance compared with those of normal methods.

I. INTRODUCTION

Les méthodes actuellement utilisées pour établir la granulométrie d'un brouillard consistent toutes à capter les gouttelettes sur un support et à les examiner ensuite au microscope (Davies, 1950). Le support peut être soit un fil très fin (fil d'araignée) placé dans un courant d'air de faible vitesse et chargé de brouillard, soit un support de dimensions plus importantes (lame de verre qu'on examine ensuite par transparence); dans ce cas, le courant d'air doit être suffisamment rapide pour que soit assurée la captation des gouttes de faibles dimensions.

Outre les inconvénients que peuvent présenter ces procédés (évaporation des gouttes entre captation et observation, surtout s'il s'agit d'un liquide volatile; fractionnement au moment du choc sur le support; étalement sur le support et captation imparfaite des gouttes par celui-ci) qui sont plus ou moins bien éliminés suivant les procédés expérimentaux, il est très difficile, quelque soit le dispositif employé de se

faire une idée de la densité du brouillard, c'est-à-dire du nombre de particules par cm^3 d'air.

Le présent travail a pour but la photographie directe et le dénombrement simultané des gouttelettes liquides en suspension dans un courant d'air passant dans le champ d'un microscope, ce qui permet d'établir une granulométrie absolue en une seule opération. La méthode employée résulte du perfectionnement d'une méthode utilisée précédemment par l'un de nous (Veret, C., 1955), qui conduisait seulement à des granulométries relatives, et n'était applicable qu'à des brouillards de densité élevée.

Principe de la méthode

Il n'est pas possible d'opérer en photographiant simplement au microscope un volume connu d'air nuageux, éclairé latéralement, car dans un brouillard de densité normale (nuages naturels ou brouillards observés à la sortie d'un pulvérisateur médicamenteux) les gouttes sont très éloignées les unes des autres par rapport à leurs dimensions; chaque cliché ne comportant que très peu de particules, il serait nécessaire de faire un très grand nombre de photographies pour disposer du nombre de mesures nécessaire à l'établissement d'une granulométrie correcte. D'autre part, les particules sont toujours en mouvement, et leur vitesse de déplacement étant amplifiée par le microscope, il faudrait prendre des instantanés très rapides. On peut photographier avec un appareil très peu grossissant des volumes notables de brouillard en utilisant des éclairs d'un dix millième de seconde. Les gouttes se comportent comme des points lumineux, leur diamètre peut être déduit du noircissement et des dimensions des taches de diffractions qui leur correspondent, leur dénombrement étant donné par le nombres de ces taches. Ce dénombrement a été fait récemment par Webb, W. L. (1956), par une semblable méthode mais cet auteur n'a pas déterminé les granulométries correspondantes. La méthode des taches de diffraction est d'ailleurs difficile à employer.

L'appareil que nous avons utilisé est un microscope à éclairage latéral avec observation sur fond noir. La Fig. 1 représente sa projection sur 3 plans de coordonnées rectangulaires; en (a) on a la projection de l'ensemble sur le plan XOZ, en (b) et (c) sont les projections correspondantes sur les plans YOZ et XOY. O_1 et O_1' représentent l'objectif et l'oculaire du microscope, P la plaque photographique (film 24×24 mm d'une chambre automatique Robot). En fait pour réduire l'encombrement, on a placé un miroir M à 45° entre l'objectif et l'oculaire de façon à couder le microscope et à réduire son encombrement, ce qui réduit en même temps les vibrations du tube. Le plan d'incidence de M, contient la directon de visée de l'objectif et l'axe du condenseur (Fig. 1d). La lumière qui vient impressionner la plaque photographique est ainsi fortement polarisée par réflexion, la vibration prépondérante étant perpendiculaire au plan d'incidence de M.

Le champ de netteté est limité en surface par la plaque photographique de côté l et en profondeur par la profondeur de champ h du microscope qui est de l'ordre de 1/10 de mm, il est représenté sur les trois plans par la surface hachurée, qui a pour valeur hl^2/G^2, G représentant le grandissement du microscope. Le grossissement de l'objectif est égal à 7, et son ouverture numérique égale à 0·2; ce qui limite à 1μ le pouvoir réparateur pour $\lambda = 0{\cdot}4\mu$, qui représente également le diamètre minimum mesurable avec l'appareil.

Le dispositif d'éclairage est constitué par la source S, tube d'un arc à mercure à

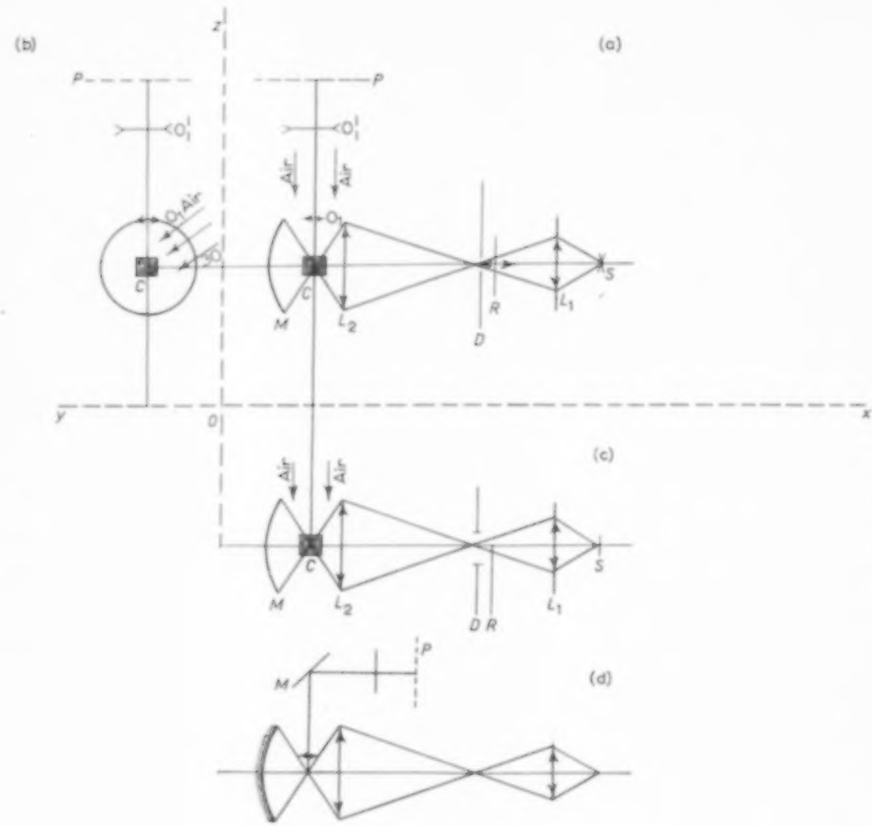


FIG. 1.

haute brillance SP 1000 alimente en courant continu. La lentille L_1 forme l'image de S sur un diaphragme D (fente allongée dans le sens du tube). L'image du diaphragme est formée dans le champ du microscope par le système L_2, et la lumière est reprise par un miroir M dont le centre de courbure est placé au centre du champ du microscope. On photographie les gouttes de brouillard qui se trouvent ainsi éclairées dans le champ de netteté du microscope.

Les gouttes sont entrainées par un courant d'air de vitesse 1 m à 2 m par sec environ, incliné à 30° sur l'horizontale, dont la direction est représentée par des flèches sur la figure. L'air passe dans le champ du microscope et les gouttes sont photographiées avant d'arriver au ventilateur; lorsque l'appareil est en équilibre de température avec l'extérieur, elles n'ont pas le temps de s'évaporer sensiblement pendant les quelques centièmes de seconde qui représentent l'intervalle de temps séparant le moment où elles sont captées à l'air libre, et celui où elles sont photographiées.

On peut connaitre la vitesse du courant d'air qui traverse le champ du microscope,

soit en la mesurant directement avec un système à fil chaud, soit en modulant le faisceau d'éclairage. A cet effet une roue dentée placée devant le diaphragme D permet d'obstruer et de dégager alternativement celui-ci, de sorte que le champ du microscope se trouve soumis à un éclairage modulé à 10^6 périodes par minute lorsqu'on fait tourner le disque. Soit v la vitesse du courant d'air. Si t est l'intervalle de temps pendant lequel on a démasqué l'appareil photographique, on verra passer dans le champ de l'appareil toutes les gouttes comprises dans le volume prismatique d'arête vt et de surface droite l^2/G^2 sin 30°.

Lorsqu'on observe au microscope des gouttes d'eau sphériques éclairées avec le système ordinaire, on peut obtenir des images circulaires nettes en faisant la mise au point sur le contour de la goutte; le diamètre de l'image est alors égal au diamètre réel de la goutte compte tenu du grandissement du microscope. Les images photographiques obtenues permettent donc de connaitre directement le diamètre des gouttelettes sans correction.

Dans ce mode d'observation, la lumière recueillie par l'objectif du microscope est transmise par la goutte qui fonctionne comme un deoptre sphérique avec ou sans réflexion interne, et comme un miroir convexe sphérique.

Si la mise au point est effectuée dans le plan diamétral de la goutte perpendiculaire à l'axe d'observation, c'est le 2ème processus qui interviendra dans la formation de l'image. L'ouverture du condensateur étant supérieure à celle de l'objectif d'observation, c'est donc celle-ci qui limite l'ouverture des faisceaux. La goutte se trouve toute entière à l'intérieur de l'image de la source donnée par le condenseur, et chacun de ses points est éclairé par un faisceau d'ouverture 2 U (U étant l'ouverture du condenseur). Tous les rayons réfléchis à la surface et pénétrant dans l'objectif sont limités par les rayons tangents à la goutte en M_1 et M_2 et faisant entre eux un angle 2 u,

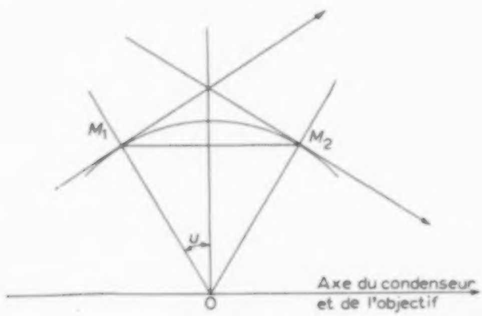


Fig. 2.

u étant égal à l'ouverture de l'objectif (Fig. 2). L'image sera donc constituée par un anneau brillant dont le diamètre extérieur est égal à celui de la goutte, et dont l'épaisseur est égale à la projection de l'arc M_1 M_2 sur le plan d'observation, ou en la circonstance sur le diamètre de la goutte perpendiculaire à la corde M_1 M_2, soit $e=R\,(1-\cos u)$. Dans le cas d'un objectif de demi-ouverture 12° on aura $e=0{\cdot}022\ R$, soit si $R=20\mu$ $e=0{\cdot}44\mu$ avec l'objectif employé ci-dessus.

Dans le présent travail on examine les gouttelettes non pas suivant l'axe du condenseur, mais perpendiculairement à celui-ci, en utilisant un condenseur d'ouverture

$2\,U=64°$ et un objectif d'ouverture $2\,u=24°$. Le champ de netteté du microscope se trouve à l'intérieur de l'image de la source (lampe SP 1000) donnée par le condenseur. Les phénomènes que l'on observe ont déjà été partiellement signalés par VERET au cours d'un travail qui n'a pas été publié. Il avait montré, dans le cas d'une goutte de faible rayon, ou dans celui d'un faible grossissement de microscope, que l'image se compose de deux points dont la distance est proportionnelle toutes choses égales d'ailleurs, au rayon de la goutte.

II. CONSTRUCTION DES IMAGES DANS LE CAS OU IL N'Y A PAS DE MIROIR SPHERIQUE

[BRICARD et DELONCLE (1958)]

Dans tout ce qui suit, nous admettrons que le diamètre de la goutte est petit par rapport aux autres dimensions qui interviennent telles que diamètre de l'objectif d'observation, distance de la goutte à cet objectif, etc. . . . et que nous sommes en présence de gouttes d'eau (indice 4/3). Les raisonnements suivants sont valables pour des gouttes d'indice quelconque, mais les résultats numériques qui dépendent de l'indice, peuvent être fortement modifiés. La mise au point est effectuée dans le plan diamétral de la goutte perpendiculaire à l'axe de l'objectif, qui contient l'axe du condenseur. Etant donné l'ouverture de l'objectif et du condenseur, on observe dans le cas de l'eau trois images d'origine différentes qui correspondent à la lumière réfléchie à la surface extérieure de la goutte, à la lumière transmise directement par la goutte et à la lumière transmise par la goutte après deux réflexions internes successives et deux réfractions (second arc-en-ciel).

(1) *Largeur des images comptée suivant un diamètre de la goutte parallèle à la direction de l'axe du condenseur*

Prenons pour plan de la figure celui qui contient l'axe du condenseur et celui de l'objectif d'observation, dont le point de rencontre est supposé coïncider avec le centre de la goutte.

(*a*) *Lumière réfléchie à la surface externe*. Considérons un point M du plan de la figure situé à la surface de la goutte (Fig. 3) sur lequel vient se former l'image d'un point de la source c'est le point de convergence d'un faisceau de demi-ouverture U; choisissons ce point M pour que l'incidence de l'axe du faisceau soit égal à 45°. Le

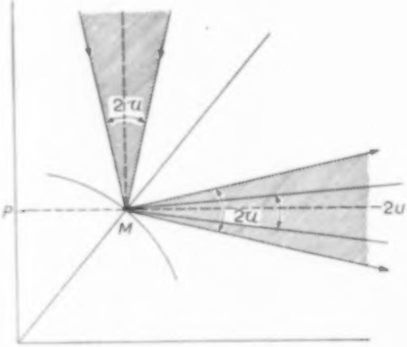


FIG. 3.

faisceau réfléchi a même ouverture U que le faisceau incident, et son axe est dévié de 90° par rapport à l'axe du faisceau incident.

L'objectif du microscope, d'ouverture u inférieure à U, diaphragme ce faisceau. Si le point M se déplace vers M′ tel que l'incidence de l'axe du faisceau incident soit inférieure à 45°, le faisceau réfléchi tourne et le point M′ reste visible dans l'objectif tant que celui-ci est frappé par les rayons réfléchis, c'est-à-dire tant que l'angle MOM′ est inférieur à $\frac{U+u}{2}$. De même, si M vient en M″ tel que l'incidence de l'axe du condenseur soit supérieur à 45°, le point M″ reste visible tant que l'angle MOM″ est inférieur à $\frac{U+u}{2}$. La largeur l, de l'image éclairée donnée par l'objectif est donc la projection m′ m″ de l'arc M′ M″, soit $R\left(\cos\left(45°-\frac{U+u}{2}\right)-\cos\left(45°+\frac{U+u}{2}\right)\right)=$ $R\,(\cos 23°-\cos 67°)=R\times 0{\cdot}53$, R désignant le rayon de la goutte.

Toutefois les points donnant lieu à un faisceau couvrant complètement l'objectif (Fig. 4) se trouvent sur une bande de largeur totale:

$$R\cos\left(45°-\frac{U-u}{2}\right)-\cos\left(45°+\frac{U-u}{2}\right)=R\times 0{\cdot}24.$$

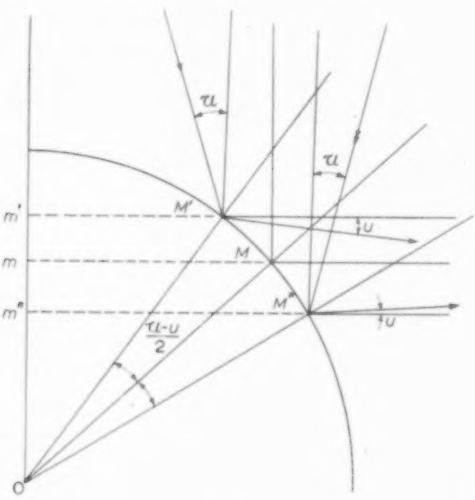


FIG. 4.

Le centre de l'image se trouve à une distance du centre de la goutte $OM=R\cos 45°=\frac{R\sqrt{2}}{2}$.

(*b*) *Lumière transmise par la goutte après deux réfractions successives.* Ces rayons émergent de la goutte après avoir subi une déviation $D=2\,(i-r)$ (i=incidence, r= réfraction). Les rayons les plus déviés arrivent en M (Fig. 5) sous l'incidence rasante, en faisant l'angle U avec l'axe du condenseur, leur normale faisant l'angle U avec

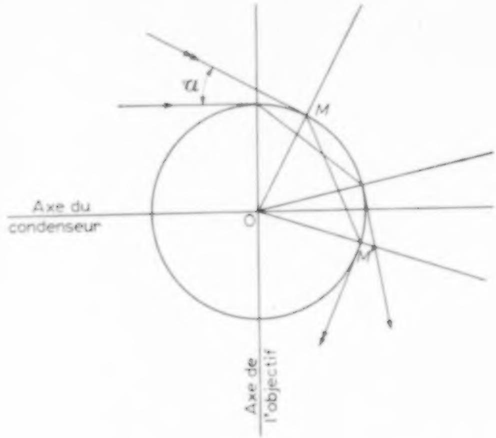


FIG. 5.

l'axe de l'objectif. Pour l'eau $\left(n = \frac{4}{3}\right)$ l'angle limite est égal à 48° 35′ de sorte que la déviation subie par ces rayons est $D = 2 \times (90° - 48°\,35') = 82°\,50'$. Ils font avec l'axe du condenseur un angle de $82°\,50' + U$. Dans l'exemple choisi cet angle est égal à $82°\,50' + 32° = 114°\,50'$. Cet angle étant supérieur à 90° les rayons ayant subi deux réfractions successives pénètrent ainsi dans l'objectif d'observation, et donnent naissance à une seconde image.

Le rayon A′ M′ MA extrême (Fig. 6) provenant du faisceau parallèle dont la direction fait l'angle U avec l'axe du condenseur et pénétrant juste dans l'objectif

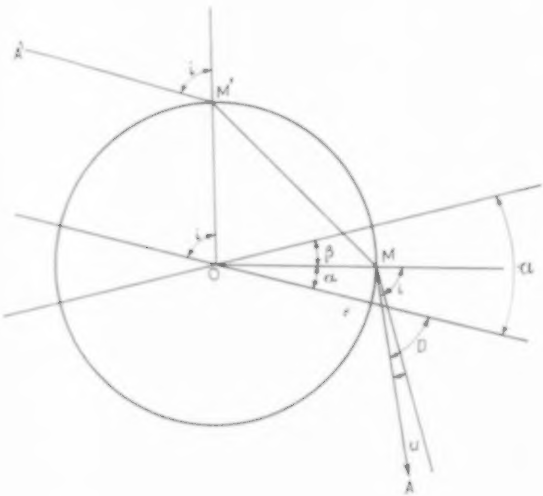


FIG. 6.

limite la largeur maxima de l'image correspondant à deux réfractions successives. La position du point M extrême est déterminée par l'angle $\beta=U-\alpha$ de OM avec l'axe du condenseur, le rayon MA émergeant en M faisant l'angle u avec l'axe de l'objectif.

Lorsque l'incidence i varie, la dérivée

$$\frac{d\alpha}{di}=2\frac{dr}{di}-1=\frac{2\cos i}{\sqrt{n^2-\sin^2 i}}-1 \tag{1}$$

est positive lorsque $i<60°$. Donc, lorsque i croit de O à 90°, α croit passe par un maximum pour $i=60°$ et décroit ensuite. L'angle β considéré ci-dessus est déterminé par les relations:

$$\begin{aligned} U+D-u &= \frac{\pi}{2} \\ D &= 2\,(i-r) \\ i &= \alpha+D \end{aligned} \tag{2}$$

ce qui donne $\beta=20°$. L'image correspondant aux rayons ayant subi deux réfractions sera ainsi limitée par le bord de la goutte opposé à la direction de la source, et aura pour largeur $l_2=R\,(1-\cos 20°)=0{\cdot}06\ R$.

(c) *Lumière transmise par la goutte après deux réflexions internes.* Il est facile de voir que dans les conditions de l'expérience, la lumière qui a subi une seule réflexion interne ne peut intervenir, la déviation minimum correspondant à un angle maximum de 41° avec l'inverse de la direction du faisceau incident dans le cas d'un faisceau parallèle n'étant pas suffisante.

Pour étudier la lumière qui a subi deux réflexions intérieures, considérons d'abord les rayons incidents parallèles à l'axe du condenseur. Le rayon venant frapper la goutte sous l'incidence i sort après deux réflexions internes en faisant un angle (Fig. 7),

$$\Delta=\pi+2i-6r \tag{3}$$

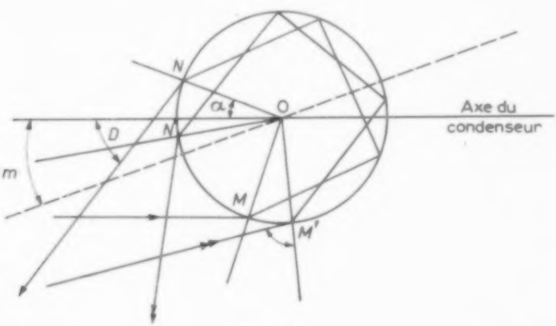


FIG. 7.

avec l'inverse de la direction du faisceau du condenseur. Cet angle est minimum, les rayons correspondants étant les rayons efficaces, lorsque l'incidence est donnée par:

$$\sin^2 i=\frac{9-n^2}{8}. \tag{4}$$

D'où $i_{eff}=72°$ et $r_{eff}=45°\ 31'$. Ceci correspond à $\Delta_m=51°$. Dans ces conditions la direction des rayons efficaces fait un angle $90°-51°=39°$ avec l'axe de l'objectif d'observation, qui est lui-même perpendiculaire à l'axe du condenseur. La demi-ouverture de cet objectif étant de 12°, le rayon considéré ci-dessus n'y pénètre pas.

Pour tenir compte de l'ouverture du condenseur, considérons un rayon incliné sur son axe et venant frapper la goutte. Soit m l'inclinaison générale de tous les rayons parallèles à cette direction, comptée positivement dans le cas indiqué par la figure 7, M le point d'incidence efficace pour les rayons parallèles à l'axe du condenseur, N le point d'émergence de ce rayon. ON fait avec la direction de l'axe du condenseur un angle $\alpha=21°$.

Le rayon frappant le point M et dont l'inclinaison sur l'axe du condenseur est m n'est pas un rayon efficace, et le point M′ correspondant à l'incidence efficace pour cette direction des rayons sera tel que OM′ fasse avec OM un angle m. La direction des rayons émergeants correspondants par rapport à l'axe du condenseur sera donnee par:

$$D=\Delta_m+m. \tag{5}$$

Dont la valeur minima $D_m=\Delta_m+U$ correspondra aux rayons extrêmes provenant du condenseur ($U=32°$) sera $D_m=83°$.

Il lui correspondra un point d'émergeance N′ tel que ON′ fasse avec la direction inverse de l'axe du condenseur un angle $\alpha-U=21°-32°=-11°$, le signe—indiquant que le point N′ se trouve du même côté de l'axe du condenseur que l'objectif d'observation.

Les rayons provenant du point M′ seront donc limités par la déviation maximum c'est à dire un angle minimum de 83° avec la direction inverse de l'axe du condenseur. Ils seront inclinés sur l'axe de l'objectif, de demi-ouverture 12° d'un angle $90°-83°=7°$; cet objectif ne sera donc que partiellement couvert par un faisceau d'ouverture $12°-7°=5°$. Les rayons pénétrant dans l'objectif se trouveront sur l'arc N′ N″$=5°$, et le point N″ sera caractérisé par un angle de $11°-5°=6°$. L'image correspondant à ces rayons sera donc pratiquement confondue à 0·02 près avec l'extrémité du diamètre de la goutte située du côté de la source. La largeur sera $l_3=R(\cos 11°-\cos 6°)$ $=R\,(0{\cdot}996-0{\cdot}982)=0{\cdot}014\,R$. Pour $R=50\mu$ ceci est égal à $0{\cdot}7\mu$ quantité inférieure au pouvoirséparateur de l'objectif utilisé en la circonstance.

En réalité, les rayons efficaces sont tangents à un cercle de rayon $r=R\sin i_{\text{eff}}=R\sin 70°=0{\cdot}94\,R$. C'est par cette valeur qu'il faut remplacer R dans le calcul ci-dessus et on commet une erreur de 6% sur le diamètre en confondant un des bords de l'image avec l'extrémité du diamètre parallèle à l'axe du condenseur placée vers la source.

(2) *Hauteur des images comptée perpendiculairement à l'axe du condenseur*

(*a*) *Lumière réfléchie à la surface extérieure*. Prenons comme plan de figure celui qui est perpendiculaire à l'axe du condenseur, et qui contient le point M de la Fig. 3, tel que l'axe du cône réfléchi en ce point soit perpendiculaire à l'axe du condenseur, sa demi-ouverture étant égale à U soit 32°. MP (Fig. 3) a pour valeur $r=R\sin 45°$ (R désignant toujours le rayon de la goutte); l'axe de l'objectif d'observation est supposé coïncider avec MP. Le phénomène étant de révolution autour de l'axe du condenseur, la réflexion se fait le long du cercle de rayon MP, et le cône réfléchi en un point M_1 voisin de M aura son axe dirigé suivant PM_1 (Fig. 8). L'objectif sera complètement couvert par tous les points de l'arc $M_1\,M_2$ tel que $MM_1=MM_2=U-u=20°$. La hauteur de l'image réfléchie en pleine lumière sera r sin $40°=R\sin 45°\times 0{\cdot}64=R\times 0{\cdot}45$. La hauteur totale de l'image sera déterminée par les points M'_1 et M'_2 tels que $MM'_1=MM'_2=U+u=44°$ et cette hauteur totale sera $h_1=r\sin 88°\simeq r$.

(*b*) *Lumière transmise après deux réfractions*. Un point de la surface de la goutte

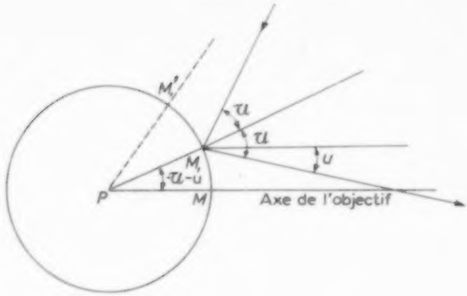


Fig. 8.

est frappé par un cône de rayon d'ouverture $U=32°$ à condition que la position de M soit telle que l'angle de OM (O étant le centre de la goutte) avec l'axe du condenseur soit inférieur à $\frac{\pi}{2}-32°=58°$. Lorsque OM_1 est perpendiculaire à l'axe du condenseur, M_1 est frappé par un demi-cône limité par le plan tangent passant par M et parallèle à l'axe du condenseur. Ce demi-cône se réduit à une génératrice tangente en OM_2 lorsque OM_2 fait un angle de 32° avec l'axe de l'objectif, soit $90°+32°=122°$ avec l'axe du condenseur (Fig. 9).

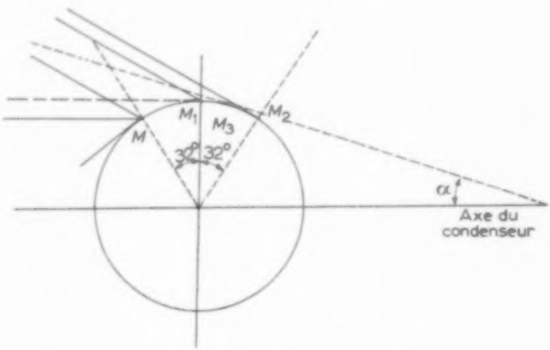


Fig. 9.

Les rayons extrêmes correspondant à M_1 situés dans le plan tangent à la goutte perpendiculaire au plan de la figure font avec la direction parallèle à l'axe du condenseur passant par M_1 un angle de 32° et sont situés de part et d'autre du plan de la figure. Les rayons émergeants se trouvent entre deux plans déterminés par ces directions et le centre de la goutte et subissent une déviation de 82° 50. Au fur et à mesure que M_1 se déplace vers M_2, l'angle que font entre eux les rayons correspondant aux rayons extrêmes contenus dans le plan tangent diminue. Ces rayons se rapprochent peu à peu et se confondent en M_2.

On peut raisonner en première approximation de la façon suivante:

On a vu que le point M extrême (Fig. 6) donnant naissance à des rayons venant frapper l'objectif correspondait à un angle $\beta=20°$. Ceci correspond pour des rayons

incidents tangents à la goutte, inclinés sur l'axe du condenseur et contenus dans un plan passant par M_3 (Fig. 9) à une déviation de 82° 50'. Le plan tangent à la goutte contenant ces rayons et perpendiculaire au plan de la figure 9, fait avec l'axe du condenseur un angle tel que:

$$\alpha=\pi/2+\beta-\delta=\pi/2+20°-82° 50' \simeq 27°.$$

Calculons l'angle des rayons extrêmes passant par le point M_3 et contenus dans ce

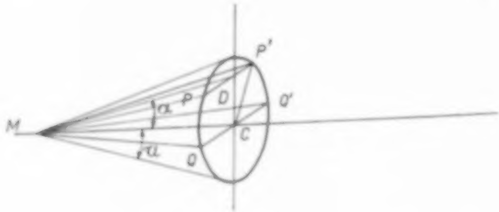


FIG. 10.

plan. Sur la Fig. 10, l'angle α est celui que font entre eux le plan MQQ' contenant l'axe du cône de demi-angle au sommet U et le plan MPP' tangent à la goutte; l'angle extrême cherché est l'angle PMP'$=\lambda$ tel que:

$$\operatorname{tg}\lambda=\frac{\mathrm{P'D}}{\mathrm{DM}}. \tag{6}$$

Il est facile de montrer sur la fig. 10 que

$$\operatorname{tg}\lambda=\cos\alpha\sqrt{\operatorname{tg}^2 U-\operatorname{tg}^2\alpha} \tag{7}$$

soit pour $\alpha=27°$ et $U=32°$, $\lambda=17° 47' \simeq 18°$.

La hauteur de l'image correspondant à deux réfractions successives vue de l'objectif sera donc limitée à une portion d'arc $2\times 18°=36°$ le long du cercle intersection de la goutte avec le plan diamétral perpendiculaire à l'axe de l'objectif. En l'assimilant à une portion de droite, sa hauteur sera $h_2=2\,R\sin 18°=2\,R\times 0{\cdot}3=0{\cdot}62\,R$.

(*c*) *Lumière transmise après deux réfractions et réflexions internes successives*. Nous avons vu lorsque nous avons calculé la largeur de l'image correspondant à la lumière transmise par la goutte après deux réflexions internes successives, et deux réfractions, que les rayons donnant naissance à l'image correspondante faisaient avec l'axe du condenseur un angle compris entre $U°$ et $U-5°$. Les premiers se réduisent à la génératrice du cône contenue dans le plan de l'axe du condenseur et de l'objectif; les seconds sont contenus dans le plan perpendiculaire à celui-ci, et faisant l'angle $32-5=27°$ avec la direction de l'axe du condenseur. Les rayons extrêmes contenus dans ce plan et pénétrant dans la goutte seront les génératrices du cône, intersection du plan en question avec le cône de demi-angle au sommet $U=32°$ et passant par le sommet du cône. En raisonnant comme dans le cas précédent, on trouve que l'angle que font entre eux ces rayons extrêmes est donné par une relation identique à (7).

La hauteur de l'image correspondant à deux réfractions successives sera donc limitée dans le cas précédent à une portion d'arc $2\times 18°$ le long du cercle intersection de la goutte avec le plan diamétral perpendiculaire à l'axe du condenseur. En l'assimilant à une portion de droite, sa hauteur totale sera $h_3=2\,R\times\sin 18°=0{\cdot}62\,R$.

Les deux images correspondant à la lumière directement transmise, et transmise

après deux réflexions successives, pratiquement identiques et symétriques par rapport au centre de la goutte, seront donc constituées par deux arcs de cercle d'une quarantaine de degrés dans l'exemple choisi.

III. INTENSITÉ LUMINEUSE ET ÉTAT DE POLARISATION DES IMAGES

(1) *Généralités*

Les dimensions des gouttelettes observées sont faibles devant les autres dimensions du système et notamment celles de la source et de son image. Dans ces conditions on peut admettre que tout se passe comme si la goutte était éclairée par un ensemble de faisceaux lumineux parallèles dont les axes convergent au centre de la goutte. Cette façon de voir rend applicable au cas présent le calcul de WIENER (1907), qui permet de connaitre, en se basant sur les lois de la réflexion et de la réfraction, l'intensité lumineuse diffusée dans l'unité d'angle solide par une goutte éclairée par un faisceau parallèle dans une direction faisant un angle quelconque avec l'axe du faisceau, et de séparer les différents processus que nous avons invoqués pour construire les images de la source données par la goutte. En fait, nous envisagerons une série d'angles α discontinus avec l'axe du condenseur variant de 5° en 5° et compris entre $-U$ et $+U$, U étant comme plus haut la demi-ouverture de celui-ci. Mais dans le système optique que nous utilisons ici, une partie seulement des rayons réfléchis et réfractés pénètre dans l'objectif et contribue à la formation des images, et c'est l'ouverture de l'objectif qui limite les dimensions des images obtenues, ainsi que l'intensité lumineuse de chacune. On a vu qu'il se forme 3 images différentes qui ne sont pas localisées dans le même plan; l'objectif est suffisamment diaphragmé et les dimensions de la goutte assez faibles pour que ces plans puissent être considérés comme confondus, et que les trois images soient nettes à la fois.

Finalement, nous calculerons l'intensité de trois images correspondant à 3 régions différentes de la surface de la goutte, et envoyant de la lumière dans des directions faisant des angles compris entre $\pm u$ (u=ouverture de l'objectif) avec la perpendiculaire à la direction de l'axe du condenseur.

Soit e l'éclairement produit à la hauteur de la goutte de rayon R par un faisceau de rayons parallèles, I l'intensité lumineuse diffusée sous un angle θ avec la direction du faisceau incident. On peut écrire pour les trois catégories d'images déterminées plus haut:

$$I = e\,\pi\,R^2\,\mathrm{f}(\theta). \tag{8}$$

La fonction f (θ) a été calculée par WIENER dans des directions faisant des angles variant de 5 en 5° avec la lumière incidente, en tenant compte de la lumière ayant subi jusqu'à 3 réflexions internes à l'intérieur de la goutte.

En fait, la goutte est éclairée par un faisceau convergent. Considérons un point O de sa section droite; l'élément de flux venant frapper la goutte et compris dans un cône d'angle solide $d\omega$ sera proportionnel à la quantité $\sin\alpha\, d\alpha\, d\varphi$ (Fig. 11). Le flux élémentaire correspondant diffusé par la goutte suivant la direction OP faisant un angle θ avec l'inverse de OM sera donc proportionnel à $\mathrm{f}(\theta)\sin\alpha\, d\alpha\, d\varphi$ et l'intensité totale diffusée par la goutte suivant OP sera proportionnelle à l'intégrale,

$$I_1 = \int_0^U \int_0^{2\pi} \mathrm{f}(\theta)\sin\alpha\, d\alpha\, d\varphi. \tag{9}$$

Pour calculer θ, le phénomène étant de révolution autour de oy, axe du condenseur

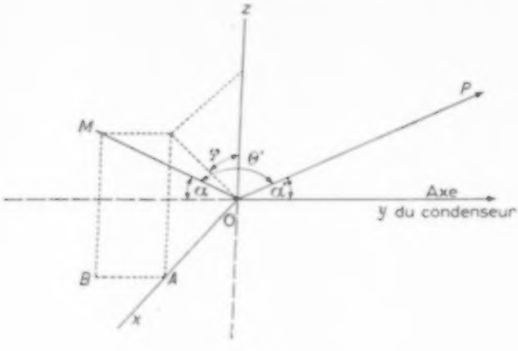


FIG. 11.

nous supposerons que OP se trouve dans le plan yoz et que la direction OP est déterminée par l'angle θ (Fig. 11). La projection du vecteur unitaire OM sur OP sera:

$$\text{Cos}\,\theta = -(\text{MB}+\text{BA}+\text{AO}) = \cos\varphi\cos\left(\frac{\pi}{2}-\alpha'\right)\sin\alpha + \cos\alpha\cos\alpha'$$

$$\cos\theta = \cos\alpha\cos\alpha' + \sin\alpha\sin\alpha'\cos\varphi. \tag{10}$$

Sur la figure, pour la commodité du dessin on a représenté l'angle $\theta' = \pi - \theta$.

Les relations ci-dessus permettent de calculer l'intensité lumineuse diffusée par la goutte éclairée en lumière convergente et observée sous un angle α' avec l'axe du faisceau en fonction de f (θ) fonction de diffusion de la goutte. L'intensité correspondant à chacune des trois images que nous avons déterminées géomètriquement, observées perpendiculairement à l'axe du faisceau aura pour expression:

$$I = \int_{-u}^{+u} I_1(\alpha')\,d\omega = \int_{-u}^{+u} 2\pi I(\alpha')\sin\left(\frac{\pi}{2}-\alpha'\right)d\alpha'. \tag{11}$$

u désignant l'ouverture de l'objectif d'observation, soit dans le cas présent $u=12°$.

(2) *Calcul de l'intensité lumineuse diffusée par la goutte par réflexion et réfraction*

(*a*) WIENER (1907) a fait le calcul complet de la fonction f (θ) en se basant sur les lois de l'optique classique. Nous rappellerons d'abord brièvement ce calcul, valable dans le cas d'un faisceau incident parallèle, et de gouttes dont le diamètre est au moins égal à 10 fois la longueur d'onde de la lumière.

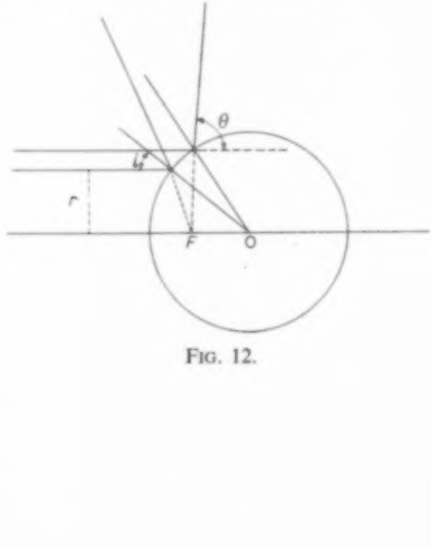


FIG. 12.

Considérons d'abord le cas de la lumière directement réfléchie à la surface externe. Soit e l'éclairement produit par le faisceau incident au niveau de la goutte; k le pouvoir réflecteur et I l'intensité lumineuse diffusée par ce processus. Le flux lumineux $d\Phi$ compris entre les deux cylindres de rayon r et $r+dr$ donne naissance au flux réfléchi $d\Phi'$ compris entre les deux cônes d'angle θ et $\theta+d\theta$ (Fig. 12). On a

$$\theta = \pi - 2i \text{ et } r = R \sin i \tag{12}$$

d'où

$$d\Phi = 2\pi\, e\, r\, d\, r = \pi e\, R^2 \sin 2\, i\, di = \frac{1}{2}\pi e R^2 \sin\theta\, d\theta \tag{13}$$

$$d\Phi' = I\, d\omega = I\, 2\pi \sin\theta\, d\theta. \tag{14}$$

De l'égalité

$$d\Phi' = k d\Phi. \tag{15}$$

On tire

$$2\pi I \sin\theta\, d\theta = \frac{k}{2}\pi e\, R^2 \sin\theta\, d\theta \tag{16}$$

d'où

$$e\, R^2\, \mathrm{f}(\theta) = \frac{1}{4} k\, e\, R^2. \tag{17}$$

L'intensité ainsi déterminée serait uniforme dans toutes les directions si le pouvoir réflecteur de la goutte était constant; en réalité, celui-ci dépend de l'angle d'incidence. Il est égal à l'unité pour $i=90°$ soit $\theta=0$ c'est pourquoi, observée dans une direction voisine de la source, la goutte éclairée parait très brillante: l'intensité correspondante a pour valeur $I_0=0{\cdot}25\, e\, R^2$, elle tombe à $0{\cdot}66\, e\, R^2$ pour $\theta=25°$.

La décroissance du pouvoir réflecteur étant plus rapide pour la vibration située dans le plan d'incidence la lumière réfléchie est donc plus riche en vibrations perpendiculaires à ce plan, elle est donc partiellement polarisée, l'état de polarisation variant avec l'incidence.

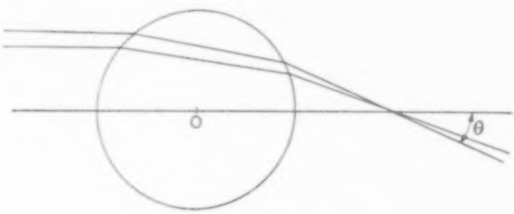


FIG. 13.

(*b*) La plus grande partie de la lumière diffusée au voisinage de la direction d'incidence est réfractée par la goutte qui fonctionne alors comme une lentille sphérique (Fig. 13). Dans ce cas, un raisonnement analogue au précédent conduit, pour l'intensité lumineuse de celle-ci, examinée sous un angle avec la direction du faisceau parallèle incident à l'expression suivante:

$$I = \frac{1}{2} te\, R^2 \frac{\sin 2i}{\sin\theta} \cdot \frac{\mathrm{d}i}{\mathrm{d}\theta} \tag{18}$$

t représentant le coefficient de transmission de la goutte.

Comme dans le cas ci-dessus, la lumière transmise par ce processus est partiellement polarisée.

(c) Une partie seulement de la lumière qui a pénétré à l'intérieur est transmise après deux réfractions successives par le processus ci-dessus. Le reste est réfléchi à l'intérieur de la goutte, et revient en arrière après une seule réflexion interne, deux réflexions internes, etc. . . . La lumière qui a subi une seule réflexion interne ne pénètre pas dans l'objectif d'observation, nous n'en tiendrons pas compte ici. Nous n'envisagerons que celle qui a subi deux réflexions internes et dont l'intensité a pour expression, en raisonnant comme dans les deux cas précédents:

$$I = \frac{1}{2}\, t\,(1-t)^2\, e\, R^2 \frac{\sin 2i}{\sin\theta} \cdot \frac{di}{d\theta}. \tag{19}$$

Il est facile de montrer que les rayons qui sortent de la goutte sont tangents à une surface caustique de révolution autour de la droite parallèle à la lumière incidente qui passe par le centre de la sphère. La méridienne de cette caustique possède une asymptote dont la direction est celle des rayons efficaces définis au paragraphe II, 1,(*c*).

AIRY a étudié théoriquement les phénomènes de diffraction qui se produisent au voisinage de cette caustique et a montré qu'il se forme un système de franges alternativement sombres et brillantes dont les déplacements et les intensités dépendent à la fois des dimensions de la goutte et de la longueur d'onde de la lumière. Le calcul de WIENER valable en toute rigueur pour un ensemble de gouttelettes, consiste à admettre une granulométrie arbitraire des gouttes diffusantes et à superposer les effets de toutes ces gouttelettes.

Dans le cas qui nous intéresse (une seule goutte de dimensions bien déterminées) ce calcul ne peut donc conduire qu'à une valeur approximative de l'intensité diffusée pour la lumière qui a subi deux réflexions internes.

(*d*) Nous observons la goutte perpendiculairement à l'axe du faisceau convergent qui l'éclaire (Fig. 11). Pour simplifier le calcul nous supposerons que l'intensité de chacune des images auxquelles elle donne lieu ne varie pas sensiblement, lorsque α' est compris entre $90°+u$ et $90°-u$; le flux lumineux reçu par l'objectif d'observation est donc proportionnel à l'intensité correspondant à $\alpha'=90°$ c'est à l'intensité lumineuse des trois images observées perpendiculairement à l'axe du faisceau éclairant.

Pour calculer l'intégrale (9), nous poserons:

$$I = \sum_0^U \sum_0^{2\pi} f(\theta) \sin\alpha\,\Delta\alpha\,\Delta\varphi \tag{20}$$

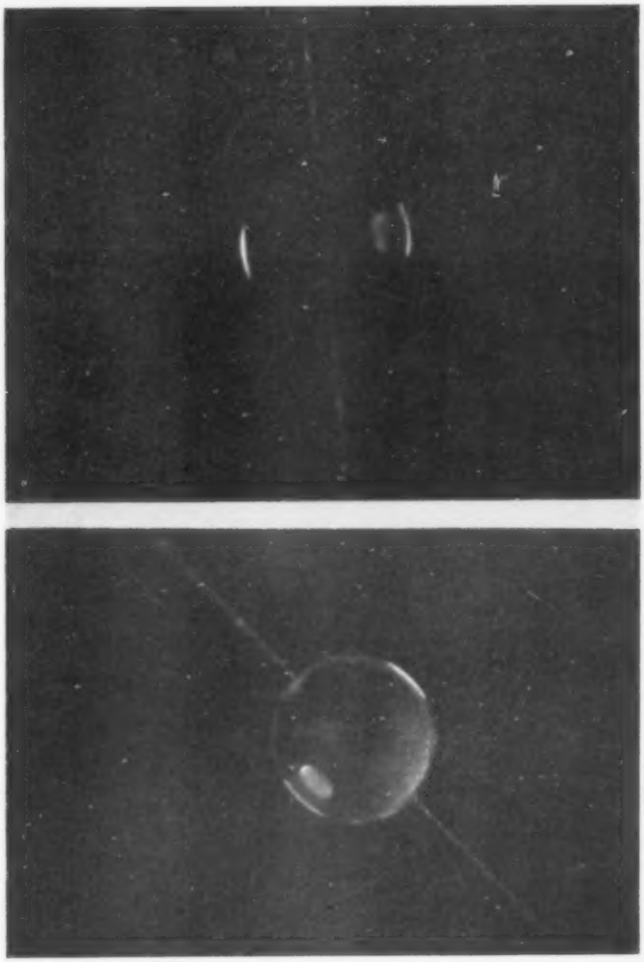
α est compris entre 0 et 30° et varie de 5° en 5°.
φ est compris entre 0 et 2π et varie de 10° en 10°.
θ est déterminé par la relation (10) dans laquelle $\alpha'=90°$,

$f(\theta)$ est emprunté à la table IV de WIENER pour les trois images correspondant à la lumière: (*a*) réfléchie à la surface externe, (*b*) transmise après deux réfractions, (*c*) transmise après deux réfractions et deux réflexions internes. On trouve ainsi que les intensités lumineuses de ces images sont proportionnelles aux valeurs suivantes:

$$i'_1 = 0{\cdot}474 \quad i'_2 = 0{\cdot}185 \quad i'_3 = 0{\cdot}071$$
$$i''_1 = 0{\cdot}048 \quad i''_2 = 0{\cdot}410 \quad i''_3 = 0{\cdot}016$$

les i' correspondent à la lumière dont la vibration est perpendiculaire au plan contenant l'axe du condenseur et la direction d'observation.

i'_1 = lumière réfléchie à la surface externe
i'_2 = lumière transmise après deux réfractions



(a)

(b)

Fig. 14.

(a) (b)

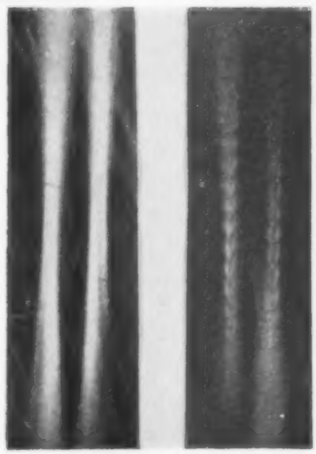


Fig. 15.

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i'_3 = lumière transmise après deux réfractions et deux réflexions internes
les i'' correspondent à la lumière dont la vibration est contenue dans le plan contenant l'axe du condenseur et la direction d'observation.

i''_1 = lumière réfléchie à la surface externe
i''_2 = lumière transmise après deux réfractions
i''_3 = lumière transmise après deux réfractions et deux réflexions internes.

Les intensités totales des trois images seront proportionnelles à:

$$i_1 = i'_1 + i''_1 = 0{\cdot}522;\ i_2 = i'_2 + i''_2 = 0{\cdot}595;\ i''_3 = 0{\cdot}087.$$

IV. ASPECTS DES IMAGES DONNES PAR L'OBJECTIF

La goutte éclairée par un faisceau convergent donne trois images constituées par trois bandes lumineuses perpendiculaires à l'axe du faisceau dont la hauteur, voisine de 0·50 R, est du même ordre de grandeur pour toutes les trois. Les largeurs de ces trois bandes sont

l_1 comprise entre 0·25 R et 0·53 R. Centre de l'image à $R/\sqrt{2}$ du centre de la goutte (lumière réfléchie à la surface externe). Hauteur $h_1 > 0{\cdot}45\ R$

$l_2 > 0{\cdot}05\ R$ contre la surface interne de la goutte, à l'opposé de la source (lumière directement transmise après deux réfractions). Hauteur $h_2 = 0{\cdot}62\ R$.

Cette largeur est sous-estimée dès que 0·05 R devient inférieur au pouvoir de résolution de l'objectif,

$$\frac{1{,}22\ \lambda}{2\mathrm{nsmu}}$$

ce qui se produit lorsque R est inférieur à 25μ.

$l_3 \sqrt{0{,}014\ R}$. Contre la surface interne de la goutte (vers la source lumineuse, lumière transmise après deux réfractions et deux réflexions internes). Hauteur $h_3 = 0{\cdot}62\ R$. Comme la précédente, cette largeur est sous-estimée car la quantité 0·014 R est toujours inférieure au pouvoir de rèsolution du microscope dans les cas qui nous intéressent.

Les éclairements de ces images, et le noircissement correspondant de la plaque photographique sont respectivement proportionnels aux quotients i/S rapport de l'intensité diffusée à la surface droite de l'image, soit pour les deux séries d'images polarisées à angle droit:

$$\text{Lumière Polarisée}\ \left\{\begin{array}{l} e'_1 = \dfrac{0{\cdot}474}{0{\cdot}22 \times \dfrac{0{\cdot}5}{0{\cdot}64}} = \dfrac{0{\cdot}474}{0{\cdot}19} = 2{\cdot}5 e'_2 = \dfrac{0{\cdot}185}{0{\cdot}05} = 3{\cdot}7 e'_3 = \dfrac{0{\cdot}071}{0{\cdot}014} = 5{\cdot}0 \\[2ex] e''_1 = \dfrac{0{\cdot}049}{0{\cdot}22 \times \dfrac{0{\cdot}5}{0{\cdot}64}} = \dfrac{0{\cdot}049}{0{\cdot}19} = 0{\cdot}26 e''_2 = \dfrac{0{\cdot}410}{0{\cdot}05} = 8{\cdot}2 e''_3 = \dfrac{0{\cdot}016}{0{\cdot}014} = 1{\cdot}0 \end{array}\right.$$

Lumière naturelle

$$e_1 = 2{\cdot}76 \quad e_2 = 11{\cdot}9 \quad e_3 = 6{\cdot}0.$$

Ces quantités sont indépendantes du rayon de la goutte tant que l_1, l_2, l_3 sont supérieurs au pouvoir de résolution du microscope, elles diminuent avec le rayon des gouttes, croissant lorsque ce rayon diminue, et représentent aussi des limites supérieures; les valeurs de e'_1 et e'_2 surtout e'_3 correspondant aux dimensions des gouttelettes nuageuses sont notablement inférieures à celles-ci. On peut en conclure,

en moyenne, que touts ces eclairements, surtout en ce qui concerne les e', sont sensiblement la même valeur. On voit d'autre part, que ces images sont fortement polarisées, notamment en ce qui concernels e_1.

Ceci se vérifie qualitativement sur la Fig. 14 qui représente la photographie avec ce dispositif d'une goutte de 100μ constituée par une solution de glycérine dans l'eau, de concentration suffisante pour éviter l'évaporation, et fixée sur un fil d'araignée. La Fig. 14 a correspond aux images e''_1, e''_2, e''_3 et la Fig. 14b représente la goutte en lumière naturelle.

V. IMAGES DONNÉES PAR L'APPAREIL COMPLET

Considérons d'abord une goutte immobile. L'addition du miroir M a pour effet de créer un système d'images identique au précédent, et symètrique de celui-ci par rapport au centre de la goutte. On a ainsi 4 images différentes symètriques, e_1 et e_3 se superposant sur la même; en moyenne, ces 4 images ont à peu près le même eclairement et donnent lieu au même noircissement sur la plaque photographique.

Lorsque les gouttes sont mises en mouvement par le courant d'air, le déplacement a lieu perpendiculairement à l'axe du condenseur, c'est-à-dire parallèlement à la longeur des images. Celles-ci donnent naissance à quartre traces distinctes et nettes tant que la goutte reste dans le champ de netteté du microscope. L'aspect de la goutte correspond ainsi à la Fig. 15a et 15b qui représentent le passage d'une goutte d'une centaine de μ de diamètre la première en lumière continue, la seconde en lumière modulée.

Les essais qui ont été faits avec cet appareil montrent qu'il est capable de détecter des gouttes dont le diamètre inférieur peut atteindre 3μ. Dans une chambre à brouillard

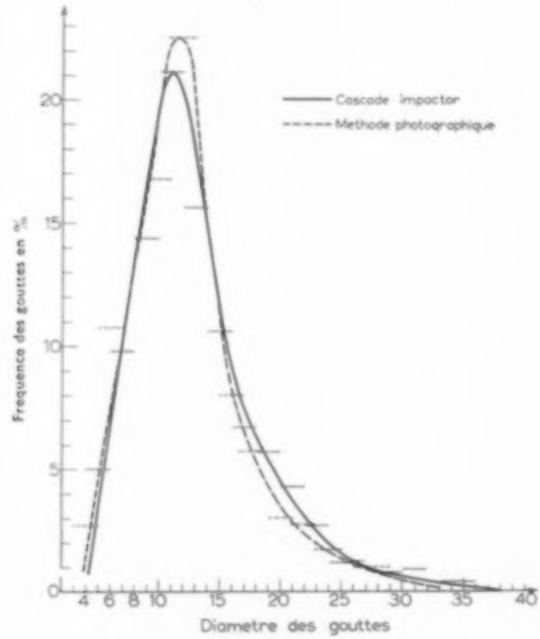

FIG. 16.

artificiel, avec un brouillard correspondant à une masse d'eau condensée de 1 gr par m3 et des gouttes dont la granulométrie est sensiblement la même que celle d'un nuage naturel, on a un nombre de gouttes convenable sur les photos en démasquant le microscope pendant 1 seconde environ. On obtiendra donc des granulométries correctes dans les nuages naturels (0·3 à 0·5 grs d'eau par m^3) en démasquant l'objectif pendant quelques secondes, durée que l'on peut régler avec une précision suffisante.

La Fig. 16 représente les granulométries relatives obtenues avec cet appareil et un Cascade Impactor dans un tel brouillard (on opère en milieu saturé et il n'y a pas de risque d'évaporation dans le Cascade Impactor) l'appareil étant éclairé en lumière continue (il n'est pas possible de réaliser des brouillards artificiels stables comportant une masse d'eau condensée suffisamment faible pour que la modulation soit utilisable). On voit que les granulométries sont parfaitement concordantes. On trouve en moyenne 800 gouttes/cm^3.

Cet appareil a pu être réalisé grâce à l'appui financier du Ministère de l'Air. Nous sommes vivement reconnaissants à Monsieur l'Ingénieur Général Vernotte d'avoir bien voulu s'intéresser à ce travail.

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SOME OBSERVATIONS ON THE INCIDENCE AND TREATMENT OF BACK INJURIES IN INDUSTRY

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(From a paper read at the Joint Meeting of the British Occupational Hygiene Society and the Ergonomics Research Society, in June 1958)

Unusual opportunities occur at Slough for the evaluation of the treatment of various injuries. It is possible for the doctor who has treated an injured worker at the time of an accident to be present at a consultation with the orthopaedic surgeon and in appropriate cases to follow the patient's progress during rehabilitation. The patient's subsequent return to work will be similarly supervised and where necessary a course of training at the Government Training Centre can be arranged.

An analysis was made of all attendances for back injuries in a large confectionery firm and for the same period a similar survey was made of back injuries reporting to the clinics of the Service from a number of smaller firms (Table 1).

Table 1. Reported accidents of the back

Cause	Firm "A"	Clinics
	(Pop. 1800)	(Pop. 11,000)
Lifting	13	17
Slipping	9	5
Conveyor belt	5	—
Falling objects	2	3
Moving truck	1	2
Fall from roof	—	1
Struck against stationary object	1	—
Total	31	28
Percentage of all strains	39	31

The period under consideration covers three months only. It is hoped at a later stage to analyse the incidence and results of treatment of back injuries over a 5-year or even a 10-year period.

When population at risk is taken into account it will be seen that there is a marked difference in incidence, or at least in the numbers reporting, the rate in the large factory with a medical department being apparently very much higher than that in

the surrounding smaller factories whose patients attend the general clinics and dressing station of the Slough Industrial Health Service.

There are several reasons for this, and they serve to illustrate the difficulty of comparing figures in different reports on the incidence of accidents.

In the factory with a medical department the workers are encouraged to report every injury, however trivial, and do not hesitate to do so. Many of those appearing in our list were very mild indeed. In the smaller firms the workers are more likely to be treated by the first-aid worker, to treat themselves, or to go to their own doctors.

There is a generous social security scheme in existence in this particular factory, and it may be that some of the back strains that occur at home during the week-end can more profitably be attributed to a strain at work on Monday.

This factory has a metalled floor which unfortunately will never wear out, but on which workers slip comparatively easily. In this connection it is interesting to note that there is double the incidence of slipping accidents in those sections of the factory where the processes require high humidity and consequently the floors tend to be slightly wet.

Another point of interest is that women, who do not after all tend to wear sensible shoes, have a lower incidence of slipping injuries than the men. It seems that men are more likely to ignore instructions not to run in corridors and some of the slipping injuries probably result from mild horse-play in changing rooms, although often these are not admitted.

These figures from "light" industry show that about a third of all strains reported are of the back, and this accords with the figures available from "heavy" industry—Dr. Trevethick finding that one-third of strains resulting in lost time were of the back. (I am aware that here we are comparing incidence with lost time, but the proportions are the same.) (Trevethick, 1958.)

In other words there does not appear to be the difference that one might expect in incidence of back injuries as between "light" and "heavy" industry. Again, reasons can be suggested—more lifting apparatus such as blocks and tackle, is likely to be available in recognized heavy work; the tougher, more heavily-built man will probably gravitate to what is recognized as "heavy" work, while a less fit individual may find himself loading packing cases on to the tailboard of a lorry in a "light" engineering works.

In the series of back injuries most of the recognized causes of these accidents are represented; e.g. two men of differing build carrying a heavy packing case, lack of co-ordination (language difficulty) between two men swinging some heavy object on to a lorry, bad lifting techniques and a lightly-built man tackling a job that is beyond him. This is illustrated by an office worker who decided to move a heavy filing cabinet; instead of waiting for the house service men, he tackled the task himself, with the result that he strained his back and was later found to have a prolapse of an intervertebral disk (Seager, 1958).

In a 3-year survey carried out in America in the Bell telephone system, 1739 back injuries were investigated. It was found that one-half of all industrial back injuries occurred in the first 2 years of specific job assignment. In most cases the length of time on the job parallels the length of service and that in turn parallels the age. In other words (in this survey) the largest number of these injuries occur among workers at an age when the general physique, musculature and other supporting structures of

the back are in optimum condition. This in turn would suggest that faulty work performance is more important than the physical condition of the person (WILKINS *et al.*, 1957).

It must be admitted that apart from the case of a prolapsed intervertebral disk or a fracture of a vertebra it is difficult to make a genuine diagnosis in most back strains. It is easy to talk confidently about a strained ligament or a pulled muscle, but in most cases it is not possible to say exactly what has happened. The term "fibrositis" merely covers ignorance, and "lumbago" at least has the merit of not implying any knowledge of the actual pathological process. However, the patient needs to be given a confident diagnosis and the term "strained muscle" or "pulled ligament" satisfies him.

Most of these minor strains clear up fairly quickly if the patients are given physiotherapy on the very day of occurrence. If necessary alternative work can be found for him. (The word "alternative" is stressed; the phrase "light work" may induce a habit in the patient of which it may be difficult to be rid, and so is best avoided.)

The patient with a prolapsed intervertebral disc will require treatment according to the severity of the particular case; some clear up after a course of physiotherapy and exercises, others may need traction, plaster of Paris jackets, or corsets. Some will be operated on. Fractures of the spine will be treated in hospital departments and the details need not be considered here.

Farnham Park is a rehabilitation centre to which people with a variety of different conditions are admitted either as out-patients attending daily, or as in-patients. Fortunately there are not sufficient accidents occurring locally to keep the Centre busy, and the majority of in-patients are from hospitals, many from the London teaching hospitals. At the Centre patients are medically examined and placed in one of three grades, a classification which decides the nature of the exercises and duration of the working day—those in the lowest grade having a rest period during the afternoon.

During the last year 44 patients with back injuries were admitted, of which 31 had prolapse of an intervertebral disk, and of this number 23 had had an operation, i.e. a laminectomy or a spinal fusion (in all these cases the original diagnosis being proved correct). Ten had fractures of the spine, and three had severe bruising resulting from falls or other accidents and required rehabilitation. Among those with fractures, there were steeplejacks and builders who had fallen from a height, others involved in accidents such as falling bars and moving trucks in the docks, and motor-cycle accidents. There appears to be some reluctance on the part of steeplejacks and steel erectors to wear safety belts, and one of the factors militating against their use is the weight of the standard leather types with metal buckles (13 lb). A new type has been designed, of nylon and terylene, which weighs only $2\frac{1}{2}$ lb. These are now being produced and their increased use would prevent some of the injuries under discussion. (Described in *Safety Equipment and Industrial Clothing*, Vol. IV, No. VII, p. 352, July 1958.)

One patient had a fractured apophyseal facet. He was an ambulance driver who had injured himself lifting a heavy patient.

Two remedial gymnasts take the patients in group and individual classes; the exercises are designed in the early stages to strengthen the long muscles of the back, and when these have been sufficiently toned up other exercises are introduced to increase mobility of the spine (Figs. 1, 2 and 3).

FIG. 1. Group exercises to increase mobility of the spine.

FIG. 2. Individual exercises to strengthen the long muscles of the back.

FIG. 3. A more advanced individual exercise for muscle strengthening—the patient is lying across a transverse bench, his legs being supported by the remedial gymnast.

FIG. 4. A patient with a fracture of the spine and pareses of the right psoas muscle. The treadle is being worked with the left foot. The paresed muscle is being exercised in the action of trunk maintenance.

Fig. 5. A patient with a back injury (P.I.D.) working at a loom and showing well the correct posture.

Fig. 6. Cross-cut sawing is an excellent exercise for the muscles of the back.

FIG. 7. A trainee can be seen in the centre of the photograph moving a cylinder in the correct manner.

FIG. 8. Some centre lathes. The face plates and chucks can be seen fitted to the lathes and on the floor beside the machines. These chucks have to be lifted and may weigh up to 60 lb.

Hydrotherapy, using a specially-designed pool, plays an important part in the treatment, and the physiotherapy department is kept busy.

Occupational therapy is, of course, most important in rehabilitation, and this has been developed to a great degree at Farnham Park. The work is selected to exercise those muscles which are of importance in maintaining the stability of the spine and to exercise any particular group of muscles which may have been involved in the injury. One of our patients was a cartographer engaged on aerial photography for map-making. He fractured his third lumbar vertebra with paresis of the psoas muscle of the right leg. In the photograph (Fig. 4) he is seen working a foot treadle machine with the left foot; the right leg is slung and action is forced on the weak muscle (trunk maintenance). He made an excellent recovery and is back on his old job.

One of the most useful forms of therapy for back injuries is work on a loom, provided the correct posture is adopted. A housewife with a prolapsed intervertebral disk (Fig. 5) is using the loom in the correct manner, the arms are wide apart and every downward movement on the beater (transverse bar) ensures contraction of the long muscles of the spine.

Another case was that of a railway fireman who fell off his engine tender platform and fractured some lumbar vertebrae. For a whole year before admission to Farnham Park he had done no work at all. He was retrained on high bench work to help restore his confidence. At a later stage he started training at the Government Training Centre, where he did bench work at a machine specially mounted on a lorry about 5 ft from the ground. In this way he became accustomed to working at this higher level, fully regained his confidence, and after 6 months as a storeman with British Railways has returned to his original job as a fireman.

Cross-cut sawing is an excellent exercise for the spinal muscles (Fig. 6).

Of the number admitted to Farnham Park, 26 returned to their former employment, including a scaffolder who had fallen 50 ft! Ten were retrained in clerical work, as piano bench fitters (action makers) and as messengers. The remainder have not recovered or have not replied to follow-up letters requesting information as to progress.

A Government Training Centre is an establishment run by the Ministry of Labour, where special training courses are available and where special regard is paid to retraining the disabled. A weekly conference is held at the Government Training Centre at which Dr. EAGGER, the Medical Director of Farnham Park, can discuss the appropriate training for patients about to leave the rehabilitation centre. The individuals are assessed as to their suitability and attainments. Some of the courses available, such as wireless and television repairing and draughtsmanship, require a comparatively advanced educational level and intelligence.

The type of training, in addition, has to be related to the man's physical condition and to the prospects of employment in the district in which he intends to live and work. Compromises have to be made.

A man recovering from a back injury can quite well be trained in the repair of wireless and television sets as long as he is working at a bench. However, he would be unable, in subsequent employment, to carry television sets up and down stairs in private houses and blocks of flats. Such training would be unsuitable unless appropriate bench work could be obtained in his home area.

In a year there were twenty-five men with back injuries trained for fresh occupations, and as they are in the disabled category they all have medical examinations and so

are seen by the Medical Officer. In this group there were approximately twice as many P.I.D's as fractures. They were trained as instrument-makers, oxyacetylene welders, draughtsmen, general fitters and machine operators (e.g. centre lathe turners) and in coach painting and watch and clock repairing. One commenced in training as a repairer of agricultural machinery. Owing to the bending and awkward positions it was not considered a suitable job. However, as for various reasons a typewriter mechanic's course was the only alternative, and he was opposed to this, he was allowed to start. As was foreseen he was unable to complete the course, which was terminated on medical grounds. With the exception of three others who terminated their courses on their own initiative, the remainder were all placed in various industries.

Although the Training Centre is run on the lines of a working factory, the instructors are all knowledgeable people with an accumulated experience of handling disabled people. Those trainees with back injuries are taught the correct way to lift and instructed to obtain assistance when required. For instance, a trainee in oxyacetylene welding (Fig. 7) will have to move gas cylinders at various times. These, containing dissolved acetylene or oxygen, weigh, when full, from 160 to 200 lb. He has been taught to move keeping his back straight and giving the cylinder small pushes with his knees. Rolling it would seem convenient, but it can become a dangerous, uncontrolled obstacle, and must in any case be lifted at the end of its journey. Trolleys are also used, but some actual handling cannot be avoided.

The importance of Fig. 8 is to stress that a certain amount of lifting is inseparable from most machine operations. It is all too easy to imagine a centre lathe turner standing by a machine and just watching a piece of metal being turned. However, it must be remembered that he will have to lift and place in position a face plate (this is fairly light, 25 lb) and a chuck which may be 3-jawed or 4-jawed. These chucks weigh between 30 and 60 lb.

In the Government Training Centre we can be sure of sympathetic consideration from the staff, but there may be trouble later when the trainee starts work in a factory. In his first job the worker may be shy about drawing attention to his back trouble and may tackle tasks that are beyond him.

The Training Centre is run closely on the lines of a factory, the trainees clocking in and out and canteen meals being provided. For those with disabilities which make walking difficult, and some of those with back injuries come into this category, a 5 min concession is allowed, which means that they can stop work 5 min before the others, enabling them to avoid the rush for buses and to prevent their always being the last in the queues for the canteen.

All those who completed the course were found, or found for themselves, jobs in industry. Some firms are not opposed to taking on these workers and of course they must employ their 3 per cent of disabled workers. However, it must be recognized that a person who has had a prolapsed intervertebral disc, however it has been treated, whether by conservative methods or by operation, remains a bad risk and will probably never be able to do any heavy lifting or similar work with safety.

The attitude of a firm when employing people known to have had back injuries is bound to be coloured by its social security and sickness benefit scheme, and where these are in operation the pre-employment medical examination becomes in essence an insurance examination.

In many cases such managements will not view with favour the recruitment of

poor-risk cases, and unfortunately many people who have had back injuries come into this category.

Recommendations suggesting limits on the type of work to be carried out can be made. Firms, however, often have difficulty in finding suitable alternative jobs for those in need of them and already in their employment, and so are naturally loth to add to the problem by recruiting workers on whom restrictions must be placed.

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LA LUTTE CONTRE LE BRUIT: PROTECTION DES TRAVAILLEURS CONTRE LES BRUITS ET LES VIBRATIONS

Principaux points à considérer dans les locaux à usages industriels et commerciaux

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Sommaire

Malgré les améliorations incontestables apportées aux conditions d'existence de l'homme par le développement prodigieux des techniques modernes, la rançon du progrès se traduit bien souvent par une action nuisible sur l'organisme humain. Le bruit est l'une des principales et peut-être la plus importante de ces nuisances.

Cet article a pour but de signaler d'une façon générale les principaux points à considérer dans la lutte contre le bruit et sur lesquels une action peut être possible—*soit collectivement* en insonorisant les locaux par protection externe ou traitement interne, en étudiant rationnellement les sources de bruits, les opérations, et l'aménagement des postes de travail—*soit individuellement* en utilisant des bouchons d'oreilles ou des casques de protection appropriés.

Les auteurs rangent les principaux points à considérer dans toute étude entreprise en vue de réduire les bruits et les vibrations dans les locaux à usages industriels et commerciaux, en cinq rubriques distinctes:

I. *Locaux:* conception générale, construction, aménagements et améliorations.
II. *Machines, appareils et engins divers:* conception, choix, construction et améliorations.
III. *Installation et entretien des machines, appareils et engins divers:* implantation, fondations, fixations, liaison avec les autres éléments de l'installation.
IV. *Opérations et postes de travail:* étude des opérations et aménagement des postes de travail, isolation des pièces et isolation des ouvriers.
V. *Protection des ouvriers:* collective et individuelle.

Abstract

In spite of the undoubted manner in which modern techniques have made life easier for man, a toll is often exacted in terms of injury. Noise is one of the chief, perhaps the most important, of such harmful agents.

This article reviews the main lines of action which can be taken in contending against noise. The soundproofing of areas by insulation and the study of sources, to protect exposed personnel as a group, are dealt with as well as individual protection by earplugs and muffs.

The reduction of noise and vibration in industrial and commercial undertakings can be pursued in five distinct ways.

I. *The premises.* General purpose, construction, design and improvement.
II. *Machinery, apparatus, miscellaneous gear.* Purpose, selection, construction and improvement.
III. *Installation and maintenance of machinery, etc.* Mounting, foundations, attachment, connections between different parts.
IV. *Operations and working positions.* Study of operations, planning of working positions, insulation of rooms and of the workers.
V. *Protection of the workman.* Collective and personal.

INTRODUCTION

Le développement prodigieux des techniques modernes a permis, dans de multiples domaines de la science appliquée, des réalisations auxquelles nul, même parmi les

esprits les plus audacieux, n'en aurait soupçonné ou prévu l'ampleur il y a quelques années seulement, et dont les techniciens peuvent, à juste titre, s'enorgueillir.

Cependant, force nous est de reconnaître que, si les progrès réalisés ont apporté des améliorations incontestables aux conditions d'existence de l'homme, ils exercent parfois, en contrepartie, une action nuisible non négligeable.

"Le Bruit", véritable sous-produit ou réaction de notre civilisation industrielle moderne libéré par le génie maléfique de l'homme, est l'une des principales, et peut-être l'une des plus importantes, de ces nuisances.

En effet, l'intensité du bruit a crû, considérablement, depuis un demi-siècle en fonction des puissances mécaniques sur lesquelles est fondée notre économie et il n'est pas douteux que ses effets peuvent avoir, dans certains cas, des répercussions fâcheuses sur la santé et le comportement des individus, si l'on ne se préoccupe pas d'en limiter les effets nocifs ou destructeurs, tant sur le plan général, social et humain, que sur le plan professionnel.

Qui de nous n'est maintenant informé:

—de la surdité proverbiale des ouvriers chaudronniers ou des carillonneurs exposés au cours de leur travail à des bruits d'intensité et de fréquence élevées: rivetage, planage, façonnage des tôles, . . .

—de la gêne infligée aux personnes habitant à proximité d'installations ou d'ateliers bruyants: aérodromes, bancs d'essais de moteurs, garages, . . .

Le but de cet exposé n'est pas de préciser les moyens et les procédés à mettre en oeuvre pour assurer, dans les différents cas qui peuvent se présenter, une protection meilleure des travailleurs, mais de signaler d'une façon générale, en quelque sorte préliminaire, les principaux points à considérer dans la lutte contre le bruit et sur lesquels une action peut être possible:

—soit collectivement:

  —insonorisation des locaux par protection externe ou traitement interne,

  —étude rationnelle des sources de bruits (machines, appareils, engins divers, installation, entretien, . . .),

  —étude des opérations et aménagement des postes de travail;

—soit individuellement:

  —utilisation de bouchons d'oreilles, de casques de protection appropriés.

L'étude systématique et rationnelle des sources de bruits et de leurs causes peut seule permettre de déterminer dans chaque cas, en fonction des possibilités locales, les moyens et les procédés les plus propres, sinon à éliminer complètement les bruits, tout au moins à les réduire dans une mesure acceptable et d'éviter dans les conceptions préliminaires et les projets des erreurs et des mécomptes graves qu'il est parfois difficile de corriger après coup.

Nous n'entendons pas proposer au problème de l'insonorisation des solutions universelles, car elles seraient beaucoup trop générales pour être efficaces, mais seulement signaler, sous la forme d'exemples de réalisations pratiques et de leurs résultats, quelques applications des principes de base maintenant bien connus.

PRINCIPAUX POINTS A CONSIDERER

Les principaux points à considérer dans toute étude entreprise en vue de réduire les bruits et les vibrations dans les locaux à usages industriels et commerciaux peuvent, d'une manière générale, se ranger sous les cinq rubriques suivantes:

I—*Locaux:* conception générale, construction, aménagements et améliorations.
II—*Machines, appareils et engins divers:* conception, choix, construction et améliorations.
III—*Installation et entretien des machines, appareils et engins divers.*
IV—*Opérations et Postes de travail;* étude des opérations et aménagement des postes.
V—*Protection des ouvriers:* collective et individuelle.

La lutte contre le bruit ne se limite presque jamais à l'examen des questions relatives à un seul de ces cinq points et des solutions qui le concernent; mais plus généralement elle commande d'engager l'action simultanément sur tous ceux où elle est pratiquement possible et peut se révéler efficace.

I. LOCAUX

Le problème de l'aménagement des locaux contre le bruit se présente sous deux aspects différents suivant qu'il s'agit de locaux existants ou de locaux nouveaux à construire.

Si, en effet, pour les locaux existants, le spécialiste se trouve devant une situation de fait et s'il ne peut le plus souvent envisager que des améliorations de détail, il a, au contraire, toute liberté de conception avant construction pour les locaux nouveaux.

Amélioration des locaux existants

Jusqu'à ce jour, l'insonorisation des locaux à usages industriels ou commerciaux abritant des machines, des appareils, des engins ou des postes de travail bruyants, n'a guère retenu l'attention des milieux techniques professionnels intéressés.

Le bruit est trop souvent considéré comme un "mal nécessaire", une gêne inhérente à la profession et à laquelle il est difficile d'apporter un remède satisfaisant.

Il faut le regretter. La lutte contre le bruit permet, en effet, d'améliorer les conditions d'hygiène et de sécurité des ouvriers qui effectuent des travaux parfois extrêmement pénibles dans une ambiance bruyante susceptible d'influer fâcheusement sur leur comportement: augmentation de la fatigue, surdité, accroissement du nombre des accidents du travail, etc. . . .

La réduction des bruits dans les locaux trop bruyants peut être envisagée soit immédiatement, si la nécessité s'en fait sentir et si les conditions locales s'y prêtent, soit au cours de transformations ultérieures de ces locaux, ce qui permet de bénéficier des facilités que donnent les réaménagements d'ensemble et de tenir compte des projets et des développements futurs.

Il faut, à cet égard, noter que l'insonorisation des locaux de travail par traitement des murs, des sols et des plafonds à l'aide de matériaux absorbants, est particulièrement efficace pour réduire le bruit. L'intensité physique des bruits qui y règnent est, en effet,—toutes choses égales d'ailleurs—, en raison inverse du pouvoir absorbant moyen des parois de ces locaux. Cet effet est naturellement plus ou moins marqué suivant les fréquences des diverses composantes du bruit; il est généralement plus accentué pour celles qui sont les plus élevées, c'est-à-dire les plus aigues.

La Fig. 1 est une illustration de ces propriétés caractéristiques en situant deux spectres de bruit dans le champ auditif normal conventionnellement délimité par la courbe des seuils d'audition et par la courbe des seuils de la douleur. Ces spectres sont relatifs aux bruits de moteurs de compresseurs à gaz produits, d'une part dans la salle même de fonctionnement, d'autre part dans une salle voisine non insonorisée.

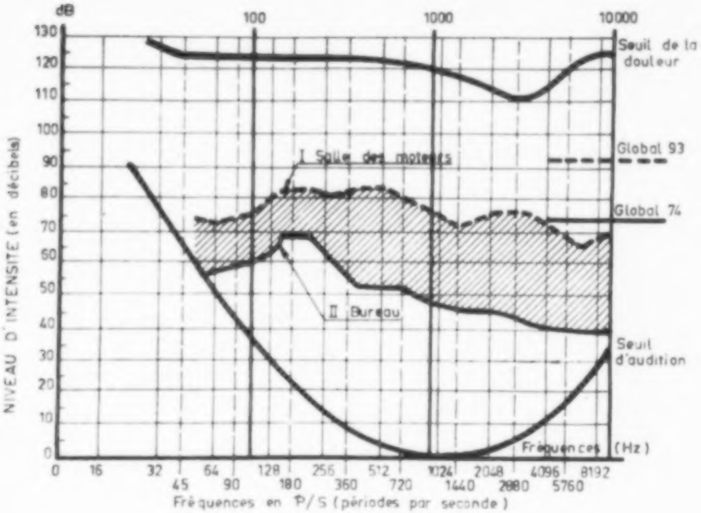

FIG. 1. Spectres du bruit.
I—Dans une salle de moteurs de compresseurs à gaz.
II—Dans le bureau attenant après insonorisation du plafond de la salle des moteurs et des cloisons de séparation des locaux.

Conception et construction des locaux nouveaux

Si, dans le passé, les locaux à usages industriels et commerciaux étaient construits sans qu'il soit tenu compte des bruits engendrés par les ateliers qu'ils devaient abriter, il n'est plus concevable actuellement qu'un architecte agisse de la sorte.

Les locaux modernes doivent être conçus, construits et disposés en fonction de leur destination et de la nature des ateliers qui y seront aménagés, tout particulièrement lorsque ces ateliers sont qualifiés de "bruyants".

Les ressources techniques que les matériaux dits insonores mettent à la disposition des architectes et des ingénieurs permettent de mener systématiquement cette étude.

C'est ainsi que l'Aviation, dont l'essor s'est révélé aussi prodigieux que la bruyance, a étudié de façon très approfondie la réduction des bruits provenant de ses bancs d'essais de moteurs. Elle a obtenu des résultats très intéressants par l'isolement des cabines de contrôle des salles de moteurs en cours d'essai. Elle y a, en outre, construit de véritables filtres acoustiques pour empêcher le bruit de rayonner au loin et d'incommoder les populations riveraines ou voisines.

La Fig. 2 est une illustration d'un type caractéristique d'insonorisation relatif à une installation de banc d'essais de turbo-réacteurs.*

On y voit notamment les ensembles de chicanes qui forment un véritable filtre acoustique laissant libre cours aux admissions d'air et à l'échappement rapide des gaz rejetés par le turbo-réacteur tout en affaiblissant les sons gênants de fréquences moyennes et de fréquences élevées.

* Communication de M. A. BOËT (Oct. 1954)—*5éme Congrés Technique National de Sécurité et d'Hygiéne du Travail*—Strasbourg.

C'est ainsi que les réductions globales d'intensité obtenues, pour un bruit qui était de 137 dB au voisinage du réacteur, sont de l'ordre de:

—36 dB, sur l'aspiration principale,

—31 dB, sur l'aspiration secondaire,

—43 dB, à la sortie de la cheminée de refoulement des gaz.

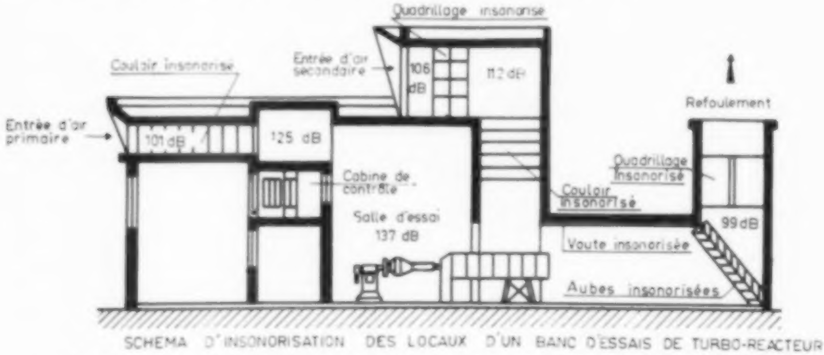

FIG. 2. Schéma d'insonorisation des locaux d'un banc d'essais de turbo-réacteur.

Ce qui a été réalisé dans ce domaine, où les intensités de bruits ont une intensité excessive atteignant 150 phones, sont parfaitement intolérables, pour l'organisme humain, tout au moins pendant un temps prolongé, peut-être adapté à de nombreuses installations industrielles où les bruits, sans atteindre de tels niveaux, n'en sont pas moins nocifs.

L'expérience a montré que des améliorations substantielles peuvent être ainsi obtenues.

II. MACHINES, APPAREILS ET ENGINS DIVERS

L'insonorisation générale des locaux, moyen efficace de réduire les bruits et d'améliorer les conditions d'ambiance qui y règnent, ne doit pas, toutefois, détourner les techniciens du problème primordial qui est l'insonorisation des générateurs de bruits proprement dits, c'est-à-dire *l'élimination des bruits à la source*.

En effet, en résolvant ce problème, en supprimant le bruit à la source, celui de l'insonorisation des locaux devient sans objet ou du moins sa difficulté se trouve diminuée dans la mesure où le premier a été mieux traité.

Les machines, appareils et engins divers méritent d'être soigneusement étudiés à cet égard. L'ingénieur doit concevoir, réaliser ou améliorer une machine pour qu'elle réponde non seulement aux impératifs d'utilisation mais qu'elle soit également assez silencieuse pour que ses bruits de fonctionnement prévisibles ne dépassent pas des limites d'ambiance acoustique considérées comme acceptables.

La méthode d'étude consiste à examiner la machine d'abord, en elle-même, comme source intrinsèque de bruit, puis dans ses relations avec les conditions topographiques et fonctionnelles d'emploi. Ce double aspect de cette étude peut être éclairé par le cas du diapason dont la fourchette vibratile ne répond aux intensités normales des sons qu'après une association avec sa caisse de résonance.

Les procédés d'investigation consistant à caractériser les bruits systématiquement par un nombre unique de décibels, puis analytiquement par des courbes représentant

la variation de l'intensité en fonction de la fréquence, permettent de substituer à l'appréciation subjective, toujours un peu incertaine, des mesures objectives d'intensité globale avec des sonomètres et des analyses spectrales susceptibles de préciser la nature des bruits. Elles donnent parfois le moyen d'identifier et de localiser la nature, l'origine des bruits gênants et ainsi d'y porter rationnellement un remède efficace.

Ces méthodes reposant sur la mesure de l'intensité globale et sur l'analyse spectrale permettent également de contrôler l'efficacité des dispositions prises pour réduire les bruits parasites et, en définitive, la valeur des résultats obtenus.

Comme pour les locaux, le problème des machines se présente sous deux aspects différents suivant que l'on envisage un état de fait ou, au contraire, une réalisation future.

Amélioration des machines, appareils ou engins existants

L'insonorisation d'une machine bruyante est un problème parfois très difficile à résoudre. Néanmoins, les résultats des mesures et des analyses rappelées précédemment mettent en valeur les conséquences particulièrement intéressantes que l'on peut attendre de l'application des dispositions appropriées auxquelles elles conduisent, car on connaît maintenant les méthodes de traitement rationnel.

La mesure à l'aide d'un sonomètre des niveaux sonores aux différentes fréquences permet de tracer une courbe caractérisant le spectre du bruit de cette machine.

L'étude de cette analyse spectrale permet de se rendre compte dans quelle bande de fréquence le niveau sonore est le plus élevé.

Le technicien orientera alors ses recherches de manière à réduire tout d'abord les niveaux de bruits les plus intenses ou les plus gênantes.

Après correction acoustique, une nouvelle mesure, à l'aide du même sonomètre, permettra de juger, d'après le nouveau spectre de bruit, l'efficacité des améliorations apportées à cette machine.

Le technicien tentera d'éliminer de proche en proche les composantes ayant dans le spectre les niveaux les plus élevés, le premier objectif à atteindre étant de ramener le niveau sonore maximum de cette machine à celui de l'ambiance générale de l'atelier.

Les spectres de bruit de la Fig. 3 relatifs aux spectres de bruit produits par un tonneau-dessableur de Fonderie, avant et après insonorisation, par revêtement de la paroi intérieure du corps cylindrique par une plaque de caoutchouc spécial "LINATEX"* sont un exemple typique de l'application de cette méthode.

Conception et construction de machines, d'appareils et d'engins nouveaux

Les constructeurs doivent s'attacher, par un examen systématique de tous les éléments entrant dans la fabrication des machines, ainsi que par une étude de leur comportement en cours de fonctionnement, à éliminer dans toute la mesure du possible les causes de bruits indésirables.

La détermination et l'analyse des bruits émis par les machines existantes peuvent renseigner utilement les techniciens sur les qualités de ces dernières et orienter leurs efforts en vue d'améliorer, de ce point de vue, leurs nouvelles fabrications.

La conception et la construction de machines de plus en plus silencieuses sont pratiquement facilitées par l'apparition de nouveaux matériaux et de nouveaux procédés de fabrication, de vérification et de contrôle permettant d'obtenir dans l'exécution une précision accrue.

* Communication des auteurs (Oct. 1952)—*3ème Congrès Technique National de Sécurité et d'Hygiène du Travail*—Avignon.

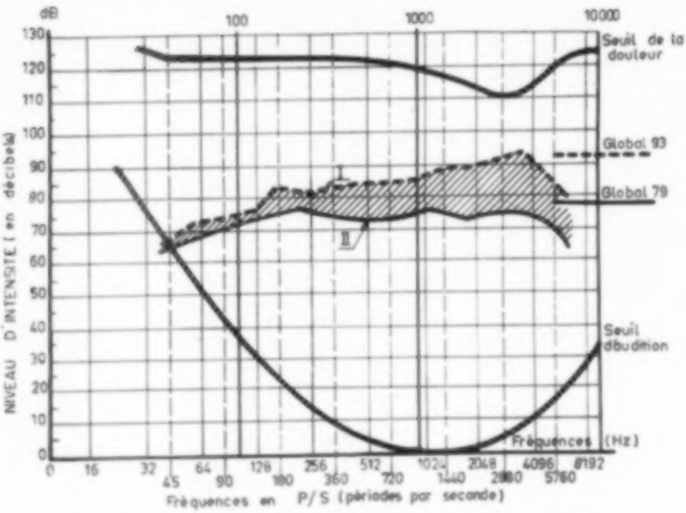

Fig. 3. Spectres de bruits d'un tonneau-dessableur de fonderie.
I—Avant insonorisation. II—Après insonorisation.

L'utilisation d'éléments ou de dispositifs tels qu'engrenages spéciaux, accouplements et suspensions élastiques, joints à un meilleur équilibrage des organes mobiles sont susceptibles d'apporter des améliorations considérables dans l'avenir.

La Fig. 4 illustre ce fait dans le cas de deux automotrices du chemin de fer métropolitain (de Paris), munies respectivement de bandages métalliques ordinaires et de pneumatiques.*

Observations

Il semble prudent d'attirer l'attention des constructeurs sur les mécomptes qui peuvent résulter d'études insuffisantes ou incomplètes de certains éléments et qui font qu'en définitive telles dispositions retenues, par exemple, dans le choix des matériaux ou dans la conception des protections risquent de renforcer le bruit au lieu de l'atténuer et s'avèrent en fin de compte plus nuisibles qu'utiles.

Les deux exemples ci-après confirment le bien-fondé de cette observation:

(1) *Caractéristiques des matériaux*. La Fig. 5 donnant les spectres de deux moteurs électriques:

—l'un de 3 cv, avec carcasse en fonte, de fabrication courante,

—l'autre de 5 cv, avec carcasse en tôle soudée, de conception moderne,

montre que si les niveaux d'intensité globale de bruit sont sensiblement les mêmes dans les deux cas, il n'en est pas de même des niveaux d'intensité en dB aux différentes fréquences.

Pour le moteur à carcasse en tôle, les niveaux d'intensité du bruit présentent dans la zône des moyennes fréquences une pointe particulièrement accentuée se rapprochant beaucoup de la courbe représentative de la douleur.

* Communication des auteurs (Oct. 1952)—*3ème Congrès Technique National de Sécurité et d'Hygiène du Travail*—Avignon.

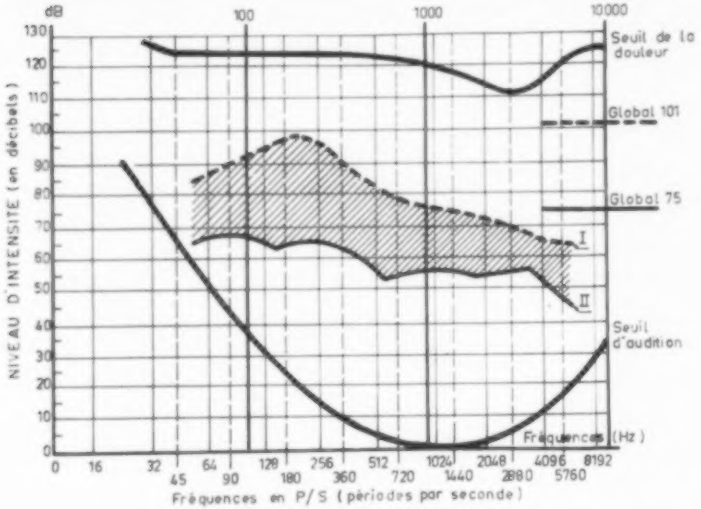

Fig. 4. Spectres de bruits pendant la marche, à l'intérieur.
I—D'une automotrice munie de roues à bandages métalliques.
II—D'une automotrice sur pneumatiques.

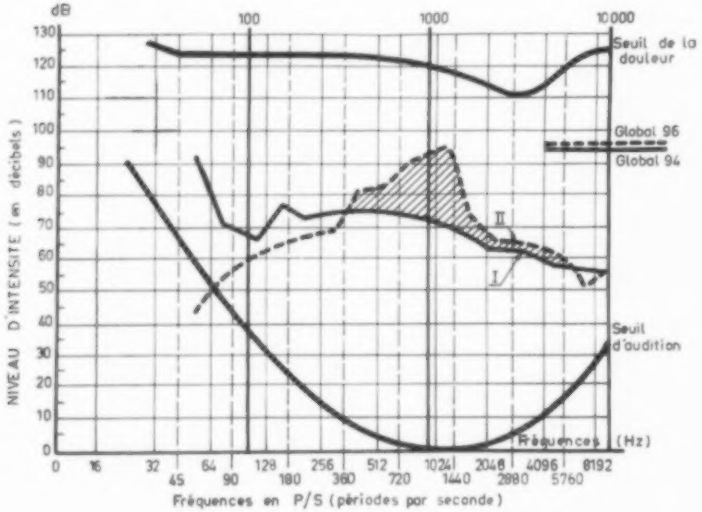

Fig. 5. Spectres de bruits.
I—Moteur 3 cv avec carcasse en fonte.
II—Moteur 5 cv avec carcasse en tôle.

(2) *Résonances accidentelles.* Les capots ou carters de protection destinés à protéger les éléments délicats et complexes de certaines machines contre les poussières, contre les contacts et les heurts accidentels susceptibles de compromettre leur bon fonctionnement ou de les détériorer, constituent le plus souvent des caisses de résonance s'ils sont mal conçus.

La Fig. 6 représentant les mesures et les analyses de bruits effectuées sur une machine perforatrice munie ou non de son capot, illustre d'une façon concrète cette constatation.

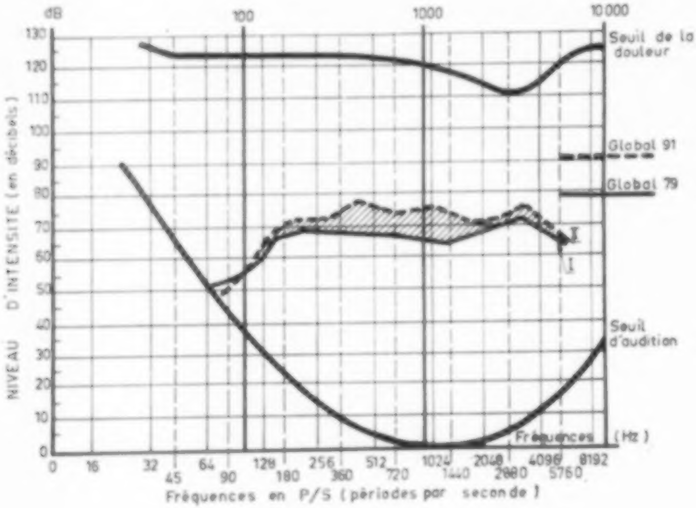

FIG. 6. Spectres de bruits d'une perforatrice.
I—Sans capot. II—Avec capot.

Dans l'étude des bruits des machines, il est très souvent utile, sinon indispensable, de localiser l'origine des bruits parasites, ce qui permet, en effet, de déterminer les parties défectueuses et d'agir systématiquement sur les imperfections.

L'utilisation de stéthoscopes industriels à réglage de fréquence peut faciliter la détection et le repérage avec précision des éléments générateurs de bruits, ce qui n'est pas toujours possible par une auscultation directe par l'oreille.

III. INSTALLATION ET ENTRETIEN DES MACHINES, APPAREILS ET ENGINS DIVERS

L'installation et l'entretien des machines doit également retenir l'attention dans la lutte contre les bruits et les vibrations.

Les bruits et les vibrations engendrés par le mouvement des organes mécaniques se propagent dans les bâtiments soit par l'air, soit par les murs, les cloisons, les planchers, les charpentes, les éléments divers produisant et transmettant les oscillations mécano-acoustiques: canalisations, transmissions, appareils de levage, de manutention et de transport, etc. . . . Leurs effets peuvent se faire sentir en des points souvent assez éloignés des sources qui les ont produits.

Pour remédier systématiquement à cette transmission et dans la mesure où elle dépend de l'installation des machines, trois problèmes sont à résoudre:

—l'implantation des machines dans les locaux,
—leur installation proprement dite (fondations, fixations, . . .),
—leurs liaisons avec les autres éléments de l'installation.

Implantation des machines

Les incidences acoustiques du problème de l'implantation des machines imposent:

—le choix d'emplacements éliminant dans toute la mesure du possible les transmissions de bruits ou de vibrations nuisibles ou gênantes;

—l'implantation des machines particulièrement bruyantes dans des cabines avec parois absorbantes et isolantes ou même à l'extérieur des ateliers.

Le souci d'un choix judicieux des emplacements des machines dans les ateliers peut faire écarter des solutions inopportunes que rien ne justifie, et apporter sans qu'il en coûte, des améliorations considérables.

Il n'est que de citer quelques exemples de machines, appareils, postes de travail: compresseurs, ventilateurs, machines à forger, etc. . . . que l'on rencontre fréquemment dans l'industrie pour comprendre toute la portée de ces observations.

Installation: fondations, fixations

Le problème de l'installation proprement dite des machines, des fondations, ou des autres éléments des bâtiments peut, en général, être résolu d'une façon satisfaisante en utilisant les matériaux anti-vibratiles, des assises amortissantes, des suspensions élastiques.

La connaissance des caractéristiques des matériaux ainsi que des caractéristiques dynamiques des machines et des spectres des bruits qu'elles produisent facilite la détermination de la solution à retenir dans chaque cas.

Les problèmes à résoudre sont parfois complexes. Aussi importe-t-il de se méfier des solutions empiriques qui ne sont pas justifiées par une étude approfondie ou par une expérience raisonnée et des extrapolations hasardeuses qui peuvent exposer à des mécomptes sérieux.

Liaison avec les autres éléments de l'installation

Une installation se compose, en général, d'une série d'éléments plus ou moins nombreux, ayant des fonctions diverses et associés entre eux pour assurer une opération déterminée.

Ces éléments, pris séparément, ont leur comportement propre comme générateurs de bruits, et, comme tels, doivent être traités individuellement. Leur association fonctionnelle peut, en outre, provoquer des réactions nouvelles dont il importe également d'envisager l'apparition et les répercussions.

La facilité de propagation des bruits et des vibrations par certains d'entre eux, tels que les canalisations et les transmissions mécaniques, impose en premier lieu, d'essayer de localiser les bruits à leur source.

L'emploi de dispositifs spécifiques, tels qu'accouplements et manchons élastiques, socles insonores antivibratiles, commandes individuelles, etc. . . . représente une des possibilités pour atteindre ce but.

Entretien

Si le bon entretien, graissage compris, des installations et des machines, conditionne leur fonctionnement, leur rendement et leur conservation, il constitue également un élément non négligeable dans l'élimination des causes de bruits.

L'usure, des pièces mobiles et tournantes, le desserrage des assemblages, la déformation éventuelle de certains éléments entraînent des jeux, des balourds, des irrégularités de fonctionnement génératrices de vibrations et de bruits.

Il suffit, pour s'en convaincre, de comparer les bruits de deux machines semblables dont l'entretien et le graissage n'ont pas fait l'objet des mêmes soins.

Ces effets peuvent être assez sensibles, comme on le voit sur la Fig. 7, par la comparaison des deux spectres de bruit de deux machines à perforer des cartes statistiques du même type, travaillant dans des conditions analogues. L'une, bien entretenue, est beaucoup plus silencieuse que l'autre.

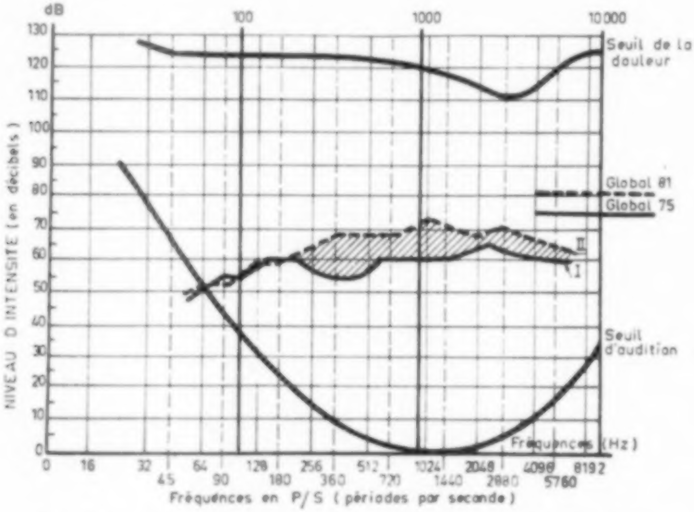

FIG. 7. Spectres du bruit de deux machines à perforer du même type. I—Machine bien entretenue. II—Machine moins bien entretenue.

IV. OPERATIONS ET POSTES DE TRAVAIL

L'étude des opérations de travail, c'est-à-dire des processus d'exécution et des manoeuvres permettant d'obtenir un résultat industriel déterminé, et l'aménagement des postes de travail, sont susceptibles de conduire, par certains de leurs aspects, à une action protectrice des travailleurs contre les bruits et les vibrations.

Les mesures prises à cet égard peuvent compléter très utilement celles qui concernent les locaux et l'installation des machines.

Etude des opérations de travail

La conception des "opérations de travail" peut avoir des répercussions sur le bruit, dans la mesure où les procédés, les machines, les appareils ou les engins mis en oeuvre sont eux-mêmes plus ou moins bruyants.

Le meilleur processus pour l'étude de ces opérations de travail devrait être déterminé:

—d'une part, en tenant compte du matériel et des possibilités d'exécution du travail, et,

—d'autre part, en tenant compte des spectres de bruits des divers éléments.

A titre d'exemples:

La Fig. 8 donnant les spectres du bruit de différentes machines: burin pneumatique, meuleuse pneumatique portative, machine à meuler à bâti fixe, susceptibles d'être

utilisées pour l'ébarbage d'une pièce de fonderie, montre la réduction du bruit qui peut résulter de l'emploi de l'une plutôt que de l'autre.

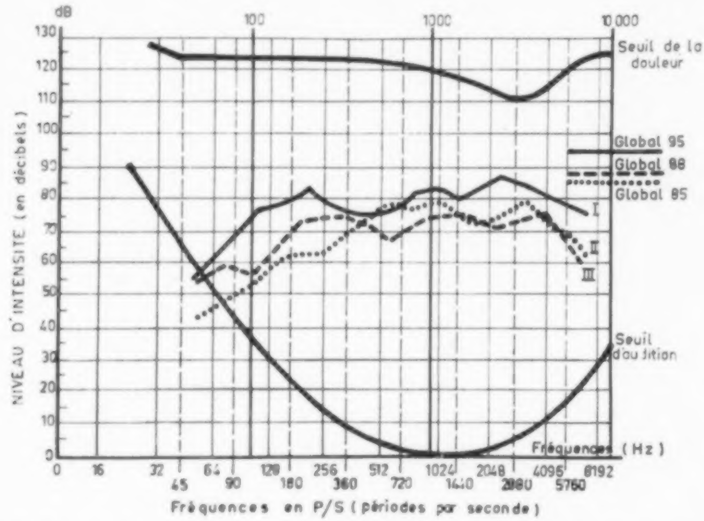

FIG. 8. Spectres du bruit au cours d'une opération d'ébarbage effectuée au moyen de.
I—Burin pneumatique.
II—Meuleuse pneumatique portative.
III—Machine à meuler à bâti fixe.

La Fig. 9, reproduisant les spectres de bruits enregistrés au cours d'une opération de démoulage sur une machine munie d'un vibreur, montre que les bruits résultant de la chute des plateaux contenant le produit à démouler, quand l'ouvrier les lancc avec force sur la table pour amorcer le décollage du produit, sont beaucoup plus intenses que ceux qui sont produits par le vibreur.

Dans ce cas, il tombe sous le sens que l'étude doit être axée sur la possibilité de supprimer le lancement brutal des plateaux plutôt que sur l'insonorisation du vibreur.

Aménagement des postes de travail

L'installation des postes de travail pose des problèmes du même ordre que ceux de l'installation des machines:

—choix des emplacements,

—aménagement des postes de travail bruyants dans des cabines insonorisées ou en dehors des locaux de travail.

Isolation des pièces en cours de travail

L'isolation des pièces susceptibles d'engendrer des bruits importants en cours d'usinage ou de fabrication doit également retenir l'attention.

L'utilisation de dispositifs appropriés: supports et suspensions élastiques ou amortissants, écrans isolants, etc. . . . peuvent, dans certains cas, limiter très efficacement la propagation des bruits et des vibrations.

C'est ainsi qu'en chaudronnerie, le remplacement des supports habituels en métal

ou en bois soutenant un corps de chaudière, par des supports munis de galets caoutchoutés, apporte une amélioration certaine.

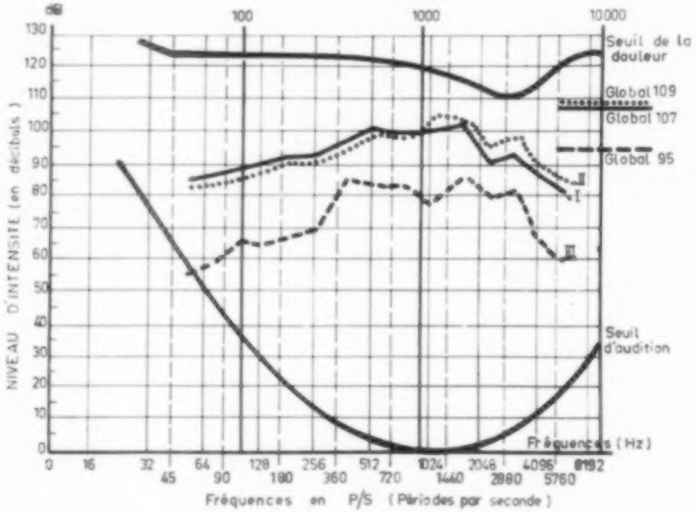

FIG. 9. Spectres du bruit d'une machine à démouler.
I—Pendant l'opération de démoulage.
II—Pendant la chute des plateaux.
III—Par le fonctionnement du vibreur seul.

Isolation des ouvriers

Les ouvriers doivent, d'une manière générale, éviter dans toute la mesure du possible de se tenir sur des éléments vibrant facilement, tels que: tôles, plaques, etc. . . .

S'il ne peut en être autrement, leur isolation est à envisager au même titre que celle des pièces, notamment par le port de chaussures à semelles élastiques, par l'emploi de planchers antivibratiles.

Il n'est pas douteux qu'un riveteur travaillant dans un corps de chaudière ressentira moins les effets des vibrations s'il se trouve sur un tapis en caoutchouc que s'il prend appui directement sur la tôle.

Conception spéciale de l'outillage à main

L'outillage à main, et tout spécialement les outils pneumatiques et électriques à vibration et percussion, peuvent engendrer des bruits et des vibrations de grande intensité et fort désagréables, voire dangereux.

Il est souhaitable que, dans l'avenir, ces outils fassent l'objet d'études systématiques tendant à les rendre plus silencieux et leur bruit moins agressif.

A égalité de service rendu, compte-tenu des caractéristiques techniques, la préférence des utilisateurs doit, en fait, aller aux outils les moins bruyants.

V. PROTECTION DES TRAVAILLEURS

La protection des travailleurs contre les bruits et les vibrations revêt deux aspects, le plus souvent liés entre eux:

—protection collective;

—protection individuelle.

Si la grande variété des moyens mis en oeuvre dans la protection collective doit, en principe, la faire considérer comme préférable et plus efficace que la protection individuelle, il est hors de doute, cependant, qu'une harmonisation logique de ces deux moyens d'action peut, dans nombre de cas, offrir une solution plus complète et plus satisfaisante.

Protection collective

En matière de protection collective, l'action doit porter sur:

—les locaux,

—les machines, appareils et engins divers,

—l'installation et l'entretien des machines, appareils et engins divers,

—les opérations et postes de travail,

qui ont fait l'objet des paragraphes précédents.

Les moyens qui tendent à la réduction des bruits à leur source et à la suppression de leurs causes, doivent avoir la priorité sur ceux qui ne visent qu'à empêcher leur propagation.

Protection individuelle

La protection individuelle consiste essentiellement à munir les travailleurs exposés à des bruits d'intensités élevées:

—soit d'un casque avec protection d'oreilles,

—soit d'un protecteur en matière spéciale, plastique de préférence, qui est introduit dans chaque oreille.

La réalisation de ces appareils: casques de protection et bouchons d'oreilles, pose des problèmes très complexes, étant donné qu'ils doivent assurer un isolement aussi parfait que possible par rapport aux bruits, sans empêcher toutefois une conversation et permettre leur utilisation avec le minimum de gêne.

Le choix du meilleur appareil, c'est-à-dire de celui qui sera le plus efficace et qui, en même temps, gênera le moins l'utilisateur, compte-tenu des conditions de travail, sera grandement facilité par l'examen comparatif des spectres de bruits des machines, et, d'une manière générale, par l'étude des ambiances de travail qualifiées de "bruyantes" et des diagrammes d'affaiblissements acoustiques des divers appareils de protection individuelle.

La Fig. 10 illustre nettement ces diverses considérations.

La Fig. 11 donne les affaiblissements acoustiques relevés sur des appareils de protection individuelle de qualités extrêmes.

Remarque importante

Il convient de noter que les mesures de protection collectives et individuelles envisagées ci-dessus doivent être complétées par une visite médicale périodique régulière, notamment du point de vue audiométrique pour contrôler l'audition des sujets exposés à des bruits intenses et prolongés.

Il est recommandé, de même, de soumettre à une visite médicale analogue les ouvriers appelés à travailler à des postes où les bruits dépassent les niveaux normalement admis, afin de préciser l'état de leur comportement auditif et de déceler les contre-indications (inaptitude de certains sujets ou danger pour eux de travailler dans des ambiances exagérément bruyantes).

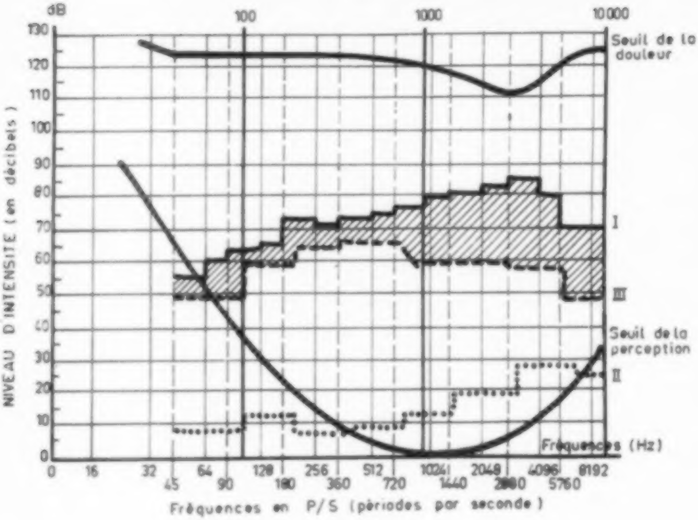

FIG. 10. Comparaison.

Courbe I—spectre du bruit d'un tonneau-dessableur de fonderie;
Courbe II—affaiblissement acoustique d'un appareil du type "bouchons d'oreilles";
Courbe III—spectre du bruit résiduel auquel est soumis l'ouvrier utilisant ce bouchon auriculaire.

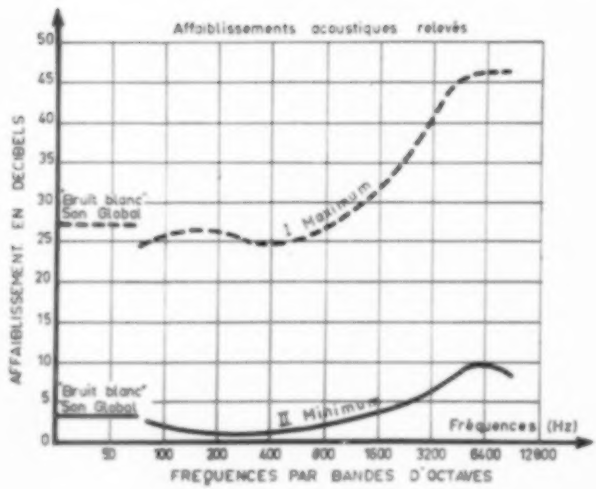

FIG. 11. Affaiblissements acoustiques relevés sur des appareils de qualités extrêmes.

CONCLUSIONS

La protection des travailleurs contre les bruits et les vibrations, malgré la difficulté des problèmes qu'elle pose, surtout lorsque la réduction des bruits et des vibrations est étudiée "*a posteriori*", comporte dans la plupart des cas des solutions pratiques grâce aux procédés et aux matériaux modernes que les nouvelles techniques d'insonorisation mettent à la disposition des réalisateurs.

Toutefois, ces solutions ne peuvent avoir leur pleine efficacité que si elles sont le fruit d'études approfondies de tous les éléments sur lesquels une action est possible, ces études étant menées au besoin en collaboration étroite par les physiciens, les architectes, les ingénieurs, les médecins, . . . Les architectes, les techniciens doivent se persuader que le bruit n'est pas un mal inévitable, une conséquence inéluctable du progrès, mais que le progrès qu'il engendre fournit en même temps le moyen d'y remédier.

Aussi bien, le "*paramètre acoustique*" doit être pris en considération dès le premier stade de l'étude d'un projet au même titre que les considérations optiques ou les caractéristiques mécaniques, électriques ou autres.

Les effets nuisibles du bruit sur la personne humaine, qui débordent dans la société moderne le cadre du travail, permettent d'affirmer que la lutte contre le bruit devient, non seulement une nécessité, mais également un devoir social.

L'Ingénieur ou le technicien chargé de lutter contre le bruit a devant lui une tâche immense et délicate. Il lui faut expérimenter avec beaucoup de prudence et d'esprit scientifique pratique. Il doit raisonner non seulement en physicien, mais souvent en physiologue, voir en psychologue, et même en sociologue. L'ensemble de ces qualités nécessaires ne peut s'acquérir que par une longue exmérience, mais avec la conviction que dans ce domaine l'ère de l'empirisme est dépassée et que la méthode scientifique y a heureusement, et avec succès, introduit et imposé un rationalisme prudent, mais efficace.

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- (1953)—Lille
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- —Chapitre I —Définitions de bruits et des vibrations
  - —Unités de mesures
  - —Mesures et analyses
- —Chapitre II —Eléments de physiologie et de pathologie des bruits

—Chapitre III—Insonorisation
—Chapitre IV—Protection individuelle contre les bruits et les vibrations
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—Commission d'étude du Bruit (Ministère de la Santé Publique et de la Population)
—Std-58-5 bis —Comité National de lutte contre le bruit (Ministère des Travaux Publics, des Transports et du Tourisme)
—Std-58-5 ter —Ligue française contre le bruit Affichage dans les Immeubles Placard "SILENCE"
—Std-58-14 —Le Médecin d'Usine (revue pratique de Médecine et Hygiène du Travail) Documentation.

FILMS CINEMATOGRAPHIQUES

Films cinématographiques sur "LE BRUIT" réalisés par l'Institut National de Sécurité:

Films techniques

1—Une réalisation de réduction des bruits sur un tonneau dessableur (Fonderie)
Durée de projection: 8 minutes

2—Une réalisation de réductions des bruits sur une automotrice (Régie Autonome des Transports Parisiens)
Durée de projection: 9 minutes

Film Actualités-Gaumont

3—Le Bruit
Durée de projection: 3 minutes

Film documentaire

4—Le Bruit
Durée de projection: 28 minutes

ANNOUNCEMENT

THE BRITISH OCCUPATIONAL HYGIENE SOCIETY

Symposium on Inhaled Particles and Vapours

An International Symposium on Inhaled Particles and Vapours, organized by the British Occupational Hygiene Society, will be held in Oxford in April 1960. The Symposium will be concerned with the physical, chemical and physiological factors governing the entry of harmful substances into the body via the respiratory system. The scope envisaged is indicated by the following provisional list of topics:

Characteristics of the respiratory system affecting deposition and retention of inhaled materials; effect of changes in activity and respiration rate; variations between individuals; animals compared with man.

Deposition of particles in the respiratory system as affected by their size, shape, density and composition; behaviour of aggregates before and after deposition; volatile and hygroscopic particles; electrified particles.

Absorption of vapours in different parts of the respiratory tract; the role of condensation nuclei. Mixtures of vapours and aerosols.

Natural processes of elimination from the lung; equilibria between intake and elimination rates for vapours, soluble and insoluble particles; times of residence; effect of rate of dosage.

Definition of a "standard" respiratory system and its simulation in sampling instruments. Methods of expressing levels of atmospheric contamination.

The subjects of the Symposium have a bearing on many hygiene problems, including silicosis, asbestosis and the other pneumoconioses, and on the damage to health produced by smog, tobacco smoke, radioactive gases and dusts, airborne bacteria and toxic vapours. The Society believes that the Symposium will meet a real need in providing an opportunity for the comprehensive discussion of recent research in this field, and that the published proceedings will be of value not only to research workers, but also to those concerned with the practical problems of establishing and maintaining safe environments.

Contributions to the Symposium will be welcomed from all countries. The main language of the Symposium will be English, but papers will be accepted, circulated in advance and published in English, French or German; interpretation in these languages will be provided for the verbal discussions. Papers submitted will be subject to scrutiny by the Society's Honorary Editor, Dr. C. N. Davies, assisted by a panel of referees.

Details of the Symposium programme and of the procedure for registration by those wishing to attend will be announced shortly.

Those wishing to contribute are requested to notify the Chairman of the Organizing Committee, Mr. W. H. Walton, Assistant Director, Mining Research Establishment, National Coal Board, Worton Hall, Worton Road, Isleworth, Middlesex, as soon as possible, indicating the subject of their papers.

Organizing Committee for the Symposium:

Chairman: Mr. W. H. Walton, Assistant Director, Mining Research Establishment, National Coal Board.

Dr. J. M. Barnes, Director, Toxicology Research Unit, Medical Research Council.

Dr. C. N. Davies, Environmental Hygiene Research Unit, Medical Research Council.

Dr. D. E. Hickish, Occupational Hygiene Laboratories, Slough Industrial Health Service.

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Dr. G. Nagelschmidt, Safety in Mines Research Establishment, Ministry of Fuel and Power.

Mr. R. J. Sherwood, Health Physics Division, Atomic Energy Research Establishment.

Dr. B. M. Wright, National Institute for Medical Research, Medical Research Council.

Mr. A. H. A. Wynn, Member, National Coal Board.

BOOK REVIEW

A. VALLAUD and P. SALMON: **Sécurité et hygiène dans l'industrie de l'huilerie.** Institut National de Sécurité, Paris, 1958. 248, pp. Fr. 200.

THE French serial publication *La practique de l'hygiène du travail* does not attempt to establish scientific treatises on occupational hygiene or toxicology. A practical and useful guide is intended for the use not merely of industrial doctors, nurses and hygienists but also of employers, workers, foremen and others responsible for the protection of the health and safety of the workers.

The series has contained treatises on benzene, carbon monoxide, chlorinated solvents, sulphuric acid and on skin diseases in the metal industry.

The present volume deals with the oil extraction industry. The first part is on extraction by pressure, the second on the apparatus and working procedures in extraction by organic solvents, particularly petrol and trichloroethylene. The third part describes the protective measures in detail, including organization of the safety service.

An addendum contains the relevant French regulations.

AAGE GRUT

NEWS

Air-pollution Control in New Jersey

In 1954 the New Jersey legislature passed its Air Pollution Control Act. Under this act an Air Pollution Control Commission is set up to prepare and promulgate detailed regulations for controlling air pollution in that state. In America much of the drive, both technical and educational, for clean air has come from our sister society the American Industrial Hygiene Association. The Association's leading place in this field is recognized by the fact that four of the nine members of the Commission are members of the AIHA, its chairman being Mr. W. R. Bradley, of the American Cyanamid Co., a past-president of the AIHA.

A Rolling Mill in the Midlands, an example of colour in industry.

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FOREWORD

THIS issue of the *Annals of Occupational Hygiene* contains the papers read at the Ninth Conference of the British Occupational Hygiene Society which was held at the London School of Hygiene and Tropical Medicine on 11 and 12 November 1958. In addition, since this aspect had not been mentioned during the Conference, Mr. J. G. HOLMES agreed to contribute an article on the lighting of outdoor installations. The Conference was followed by a visit to the factory of the Paints Division, Imperial Chemical Industries Ltd., at Slough.

Hyg. A1-3—

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VISUAL PERCEPTION

W. D. WRIGHT

Technical Optics Section, Imperial College of Science and Technology, London

THE VISUAL AXIS

As it is manifestly impossible to cover the whole subject of visual perception in one lecture, I shall deal only with those aspects which seem to me to be particularly relevant to the general theme of the Conference. For anyone requiring more complete information, reference may be made to a number of excellent modern textbooks (e.g. LE GRAND, Y., 1957; POLYAK, S. L., 1957; WOLFF, E., 1954; GIBSON, J. J., 1950).

Of outstanding importance to my mind is the existence of the visual axis. If an observer is asked to gaze steadily at a small fixation target located directly in front of him, his visual acuity (resolving power) at various distances from that target can be tested by introducing a large letter E, say, at the edge of the field and bringing it closer to the target until the observer can just recognize the direction in which the limbs of the letter are pointing. The smaller the letter, the nearer it has to be brought to the fixation target for it to be resolved. A curve can then be plotted (Fig. 1) showing the variation of the visual acuity, expressed as the inverse of the height of the letter which can be read, against the angular separation from the fixation target. The curve which is obtained rises sharply to a peak at the fixation target, and this peak defines what is known as the visual axis of the eye.

Anatomically, the existence of this peak can be attributed to the distribution of rods and cones across the retina, and to the type of nerve connections associated with the foveal and extra-foveal areas of the retina (Figs. 2, 3, 4 and 5). The fovea provides the peak acuity, thanks to the existence there of finely packed cones (Fig. 4) and a one-to-one connection between cone and nerve fibre (POLYAK, 1957). Farther from the fovea the retina is populated by a mixture of rods and cones (Fig. 5) and several of these receptors converge on to a common nerve fibre, with a consequent loss of acuity. The axis of maximum visual acuity, i.e. the visual axis, is thus the line from the centre of the fovea through the nodal point of the optical system of the eye (Fig. 2). We may note in passing that it is probably an over-simplification to regard the visual axis as precisely defined in this way, but this is a refinement of visual theory with which we need not be concerned in this lecture.

Evidently, then, the eye behaves very much like a sharp pointer, and if we wish to examine an extended scene, our eyes have to scan across the scene from point to point. We should not regard this scanning process as an orderly movement such as the scanning lines in a television system, but rather a random darting about in various directions across the scene. Neither must the scanning be thought of as a continuous movement, since the eye makes a series of jumps or saccades, with pauses between one jump and the next. This saccadic movement of the eyes is quite characteristic except when we observe a continuously moving target, in which case the eyes can follow the target in a fairly continuous "pursuit" movement.

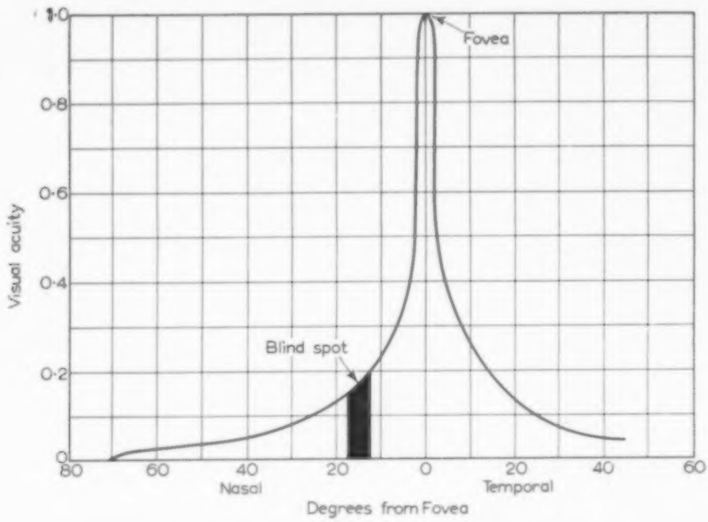

FIG. 1. Variation of visual acuity across the fovea.

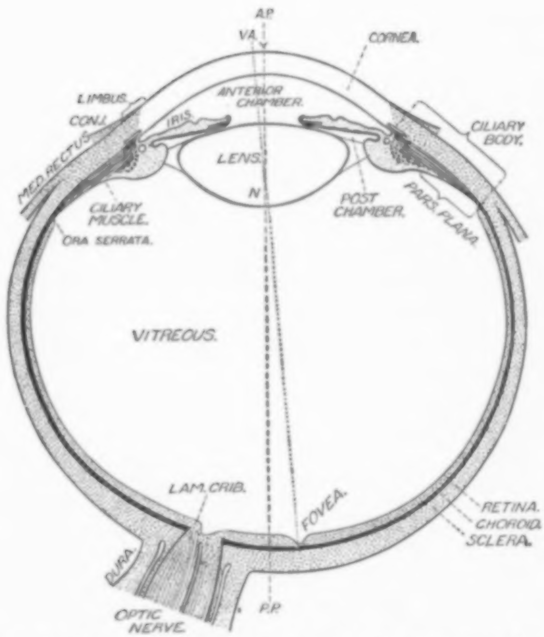

FIG. 2. Horizontal section of the eye. By permission from EUGENE WOLFF's *Anatomy of the Eye and Orbit*. H. K. Lewis, London (1954).

In the saccadic movement the actual perception occurs during the pauses when the eye rests momentarily on successive points in the scene, but it is probably wrong to regard the eyes as ever absolutely stationary. Even when gazing steadily at a small fixation target, records show that small drifts, flicks and fine vibratory movements are constantly occurring, and recent research with the stabilized retinal image (DITCHBURN and FENDER, 1955) suggests that these movements are in fact essential to vision. Thus it is possible to attach a small mirror to a contact lens placed over the eye and to view an image formed via this mirror, in such a way that the image remains fixed on the retina in spite of small movements of the eye. In such an arrangement it is found that the image almost immediately disappears but can be quickly restored once it is allowed to move across the retinal receptors again. An equivalent effect can in fact be readily demonstrated for the peripheral retina, if a small illuminated area in a dark field is projected some distance from a fixation target. If the fixation target is viewed steadily, the illuminated area is seen by peripheral vision and is effectively stationary relative to the coarse resolution of the periphery. Under these conditions, again, the illuminated patch will quickly disappear, but will immediately reappear when the eye is moved.

The process of vision is thus essentially dynamic, in which a succession of images is formed on the retina, photo-chemical decomposition occurs in the receptors, bursts of nerve impulses are transmitted up the optic nerve, and the whole pattern of nervous activity is drastically changed each time the eye makes one of its saccadic movements. We may wonder how the world we see around us can appear so stable, solid and permanent in the midst of all this visual turmoil; it is indeed a cause for wonder, and the explanation must be sought in the manner in which the information is interpreted in the visual cortex.

The existence of the visual axis must not be thought of as some oddity in the design of the visual mechanism, since without the axis our sense of direction would be very crude, we should probably find it very difficult to maintain our balance under abnormal conditions—for example, walking a tight-rope—and binocular vision and three-dimensional perception would be impossible.

We have so far considered the saccadic movements when viewing a scene as if they were almost haphazard in direction and magnitude. This may in fact be true, except that the interest and meaning in the scene may tend to focus our attention on fairly confined areas. Yet even in those cases where the movements are somewhat haphazard, the two visual axes have to be continually directed on the same points in space if double vision is to be avoided.

The movements of each eye are controlled largely by six extra-ocular muscles (Fig. 6), four rectus muscles and two oblique muscles for each eye. For the eyes to turn and rotate to a given point in the scene, the muscles have to be tensed and relaxed in tandem, and visual comfort demands exquisite co-ordination and harmony between all six pairs of muscles.

Having emphasized the outstanding importance of the visual axis, we must recognize that the peripheral retina also has a part to play in vision, and has certain special characteristics of its own. Thus it provides the general setting within which the visual axis is located and without which the relation between one area of a scene and another cannot be perceived. Further, under some levels of illumination and adaptation the periphery is more sensitive to movement than the fovea, while in the

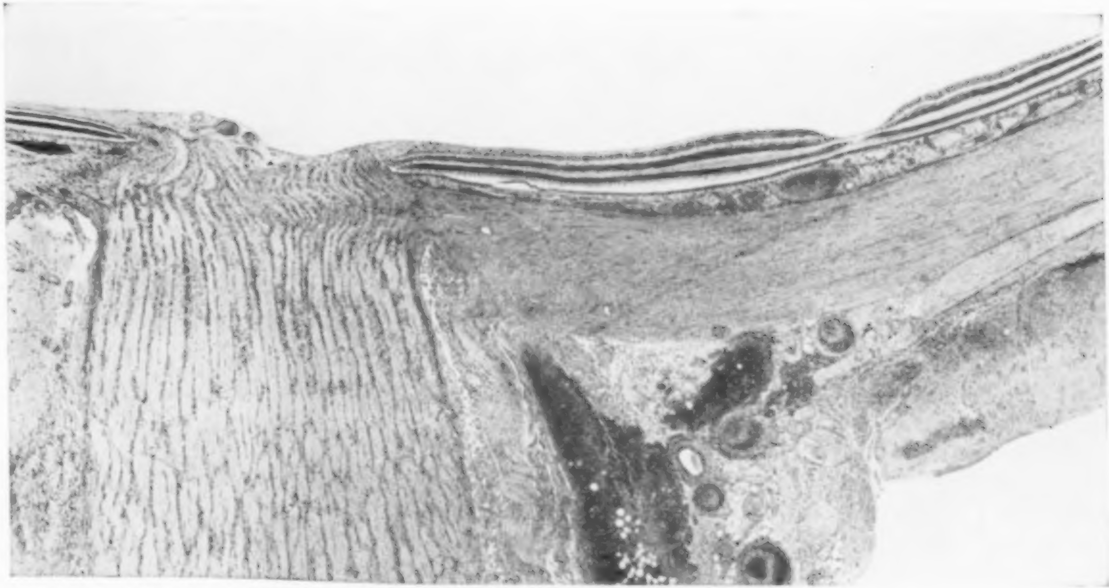

FIG. 3. Horizontal section of the optic nerve and macula, passing through the fovea centralis. By permission from EUGENE WOLFF's *Anatomy of the Eye and Orbit*. H. K. Lewis, London (1954).

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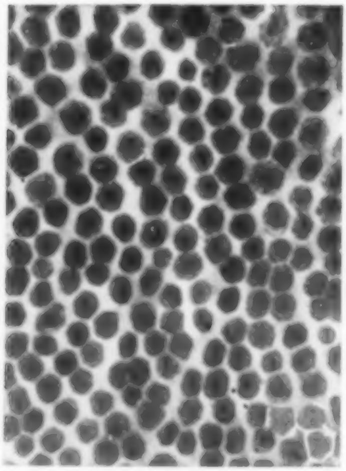
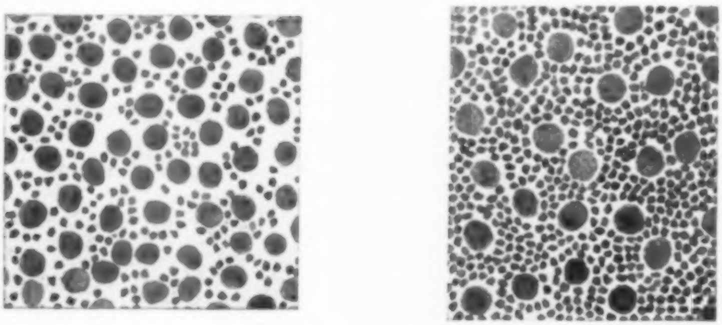


FIG. 4. The cone mosaic at the fovea. Flat section through the inner portions of the macular cones. ×1000. By permission from EUGENE WOLFF's *Anatomy of the Eye and Orbit*. H. K. Lewis, London (1954).



(a) (b)

FIG. 5. Flat section through the inner limbs of the rods (smaller) and cones (larger). × 1000.

(a) Macular region close to the rod-free area. By permission from EUGENE WOLFF's *Anatomy of the Eye and Orbit*. H. K. Lewis, London (1954).

(b) Near the macula. By permission from EUGENE WOLFF's *Anatomy of the Eye and Orbit*. H. K. Lewis, London (1954).

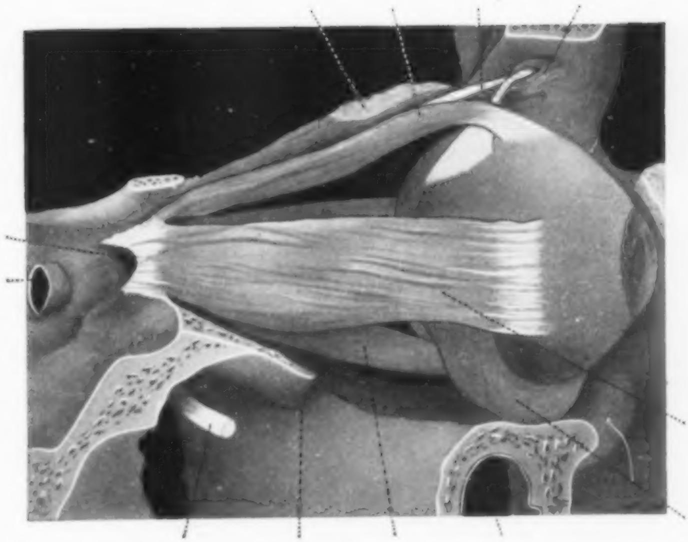


Fig. 6. Dissection to show the ocular muscles from the lateral aspect. By permission from Eugene Wolff's *Anatomy of the Eye and Orbit*. H. K. Lewis, London (1954).

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dark-adapted state, the periphery is far more light-sensitive than the fovea, as a result of the high sensitivity of the rods and the convergence of many rods on to a single nerve fibre.

VISUAL ACUITY

Although the resolving power on the visual axis reaches quite a high value, there is a finite limit to the angular separation that can just be detected between two lines or points of light. A convenient figure to take as this limit is 1 min of arc, but under good conditions of viewing and with a keen observer something rather better than this can be achieved.

There are several factors that contribute to this limit. There are physical factors such as the finite wavelength of light which prevents an exact geometrical reproduction of a fine object being imaged on the retina, while spherical and chromatic aberration in the lens system of the eye produces further blurring, and light scattered in the optic media and the retinal tissues will reduce the contrast. Then the dimensions of the foveal cones set a limit to the fineness of the retinal mosaic, and any neural convergence of two or more receptors on to a single nerve fibre will enlarge the effective dimensions of this mosaic.

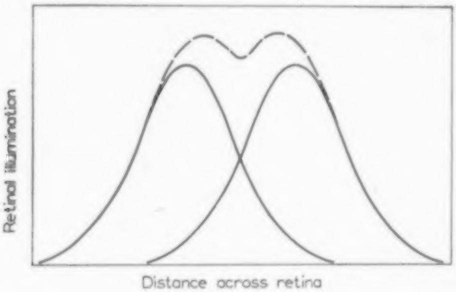

Fig. 7. Intensity distribution in retinal image of two bright lines near the resolution limit. Broken curve represents the sum of the retinal illuminations of the separate images.

However, acuity cannot be considered solely in terms of image and receptor dimensions, since the intensity distribution across the retina of the images of two bright lines near the resolving limit will be somewhat as shown in Fig. 7. To recognize that there are two narrow lines rather than one broad line requires that the observer should be able to detect the small drop in illumination in the centre of the image. Thus, in the limit, visual acuity may become as much a problem of brightness or luminance discrimination as one of angular separation. Further, if fine scanning movements of the eyes are also taking place, then a purely static concept of resolution is manifestly incomplete, and a full analysis would involve the time response of the retinal and neural processes.

This last point is of some importance since it may provide one explanation for the improvement in visual acuity that is known to occur with increase in the illumination level of the test object, since neuro-physiological studies have demonstrated that the higher the retinal illumination, the more rapid the nerve discharge. Other factors may include the smaller pupil diameter and the reduced neural convergence associated with higher light levels, while enthusiasts for information theory may claim that the

greater the amount of light entering the eye, the more the information that is available for reception in the eye and interpretation in the brain. This last factor may indeed be a valid contribution to the improved luminance and colour discrimination which is found when the areas of two surfaces being compared are increased in size.

LIGHT SENSITIVITY

Little needs to be said here about the absolute sensitivity of the eye to light, except as a further illustration of the dynamic nature of the visual process. Partly through processes of photochemical decomposition and regeneration, partly through adaptation in the neural processes, partly through transition from rod to cone vision or the reverse, the sensitivity of the eye is constantly changing as the prevailing level of illumination is changed. Thus, after a period in the dark lasting half an hour or an hour, luminances as low as 10^{-8} cd/ft^2 may just be detectable. On the other hand, when fully light-adapted, vision may still be possible in full sunlight where luminances of the order of 10^3 cd/ft^2 or more may occur.

This is an enormous range of light levels and is a tribute to the great adaptability of the eye, but it has to be recognized that the range of luminances that can be seen with comfort at any one time is very much smaller than this. There appears to be a very rapid neural adaptation process which comes into operation almost immediately a beam of light enters the eye, and this, together with the contraction of the eye pupil, makes a fairly intense illumination more immediately acceptable than it otherwise would be. Yet the full range of sensitivities is only available when time is allowed for the eye either to dark adapt (30–60 min) or light adapt (5 min) as the case may be.

Hence, where a fairly bright source is present in a field of relatively low intensity, the process of adaptation cannot be relied on to produce sufficient local retinal compensation to prevent a sensation of glare developing. The presence or absence of glare has therefore to be assessed by the range of luminances and intensities present in any given scene, while the amount of glare that can be tolerated will be a function of the distance of the glare source from the main centre of interest in the field of view.

COLOUR SENSITIVITY

The eye can only respond to a relatively narrow range of wavelengths between about 0·40μ to 0·75μ, with some extension beyond these values if sufficient energy is available. The limit at the long-wave end is set primarily by the spectral sensitivity of the photochemical substance in the cones, while at the short-wave end it is determined by absorption in the optic media. At high illumination levels in which the cones operate, the spectral sensitivity curve, Fig. 8, has its maximum in the yellow-green part of the spectrum at a wavelength of about 0·55μ. At very low illuminations, only the rods are in action and the maximum sensitivity shifts down to 0·51μ.

Colour perception is mediated through the cones, but a sensitivity curve such as that shown in Fig. 8 would not in itself provide a basis for colour discrimination, since with a single type of receptor only one quality of signal can be transmitted to the brain. For colour discrimination, at least two types of receptor are required, with sensitivity curves having their maxima in different parts of the spectrum. Colour mixture experiments suggest that in fact there must be at least three types of receptor, and typical sensitivity curves that would explain many colour phenomena are shown in Fig. 9.

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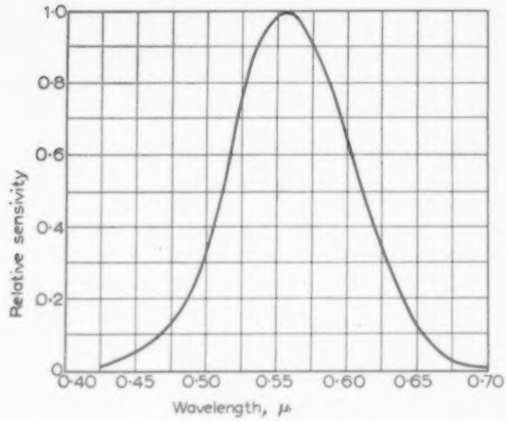

FIG. 8. Spectral sensitivity curve of foveal cones.

On this basis we can explain the perception of colour on the assumption that varying amounts of activity will occur in the red, green and blue receptors in the retina, depending on the spectral composition of the light entering the eye. In the visual cortex, corresponding centres must be stimulated by the signals from these three groups of receptors, giving rise to sensations of redness, greenness and blueness, and indeed of whiteness, yellowness and so on, depending on the relative stimulation of the centres.

These concepts have been amplified in the literature on the subject, and the technical applications have been described, for example, by the author (WRIGHT, 1958). For the purpose of this Conference, however, it is perhaps more important to

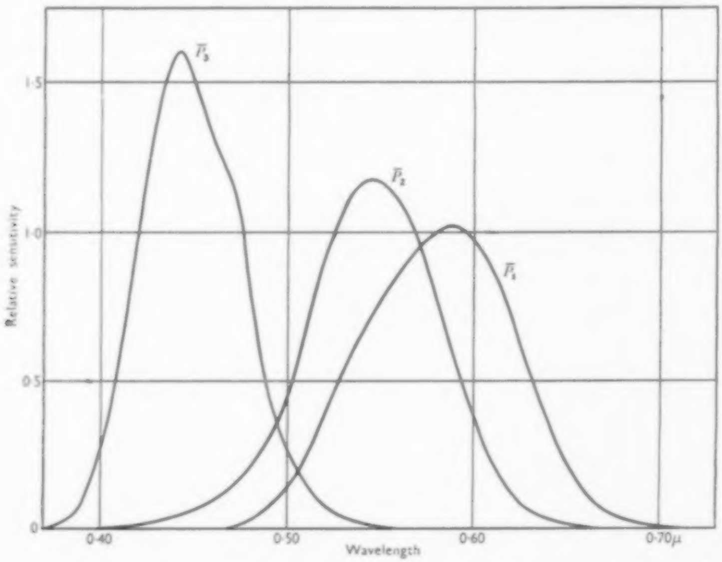

FIG. 9. Typical set of colour sensitivity curves on the three-components theory. By permission from W. D. WRIGHT'S, *The Measurement of Colour*. Hilger & Watts, London (1958).

emphasize that we are again dealing with a dynamic process and that colour adaptation can occur just as readily as light or dark adaptation. Hence the colour sensation which we may experience in some given viewing situation is not governed solely by the spectral composition of the light entering the eye, but is affected by the state of adaptation of the eye and by contrast effects with neighbouring areas in the field of view. The problem of the colour rendering of light sources, for example, involves the light being radiated by the source, the spectral reflection characteristics of the objects being illuminated and also the extent to which the colour sensitivity of the eye may adjust itself to the overall colour of the illumination.

Something should also be said about the aesthetics of colour and the therapeutic value of colour. It is, of course, quite obvious that a design can appear pleasant or unpleasant depending on the choice and balance of the colours in the design. What is not at all obvious, however, is why colours should harmonize or clash in this way. I do not believe it is possible to explain the aesthetics of colour in terms of what we know at the present time about the colour receptors in the retina or the messages they transmit to the brain. For the time being, therefore, the subject must be left very largely in the hands of the artist, where it properly belongs, but aided also by those empirical relationships which have been established over the years through the accumulated experience of designers.

Similarly, no one would deny the advantages of having, say, a ward in a hospital decorated in attractive colours, but it is quite impossible to explain, in terms of the visual processes, just how the decoration may help the patient. Again, empirical experience must be used as a guide.

Finally, we must note that as many as 8 per cent of men and perhaps 0·5 per cent of women have colour vision which is to some degree defective. With some, the defect may be so marked that it can be explained on the assumption that they possess only two colour receptors in their retina instead of the normal three, with only two sensitivity curves instead of the three shown in Fig. 9. But the essential feature of defective colour vision is a reduced ability to discriminate one colour from another. Hence, when colours are being used to convey specific information, as in a colour coding system to identify the services in a factory or the components in a radio set, special care should be used in the selection of the colours in the code. Where safety is involved, as in the recognition of signal lights, suitable colour vision tests are used to ensure that only persons with good colour vision are employed.

A study of the various industries in which good colour vision is required, was undertaken by the Physical Society Colour Group a few years ago (PHYSICAL SOCIETY, 1946). Defective colour vision can be a significant handicap in certain sections of such industries.

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DISCUSSION

The President said he wished to ask a question about the psychological aspects of vision. Was Prof. Wright of the opinion that acuity and perception were determined largely by the physiological and optical properties of the system or could they be altered by a deliberate policy of training over many years?

Prof. Wright, in reply, said he felt sure vision could be improved by training. There were, of course, physical limits to resoluton, but he felt quite sure that with training one could make better use of the information which the eye transmitted to the brain.

Just what happened in training was not too easy to explain. It was partly a question of attention to detail and partly a question of confidence. For example, it had been found in eye movement experiments that the ability to fixate varied very much according to how the subject was feeling. Sometimes it was possible to fixate and maintain the eyes steady to within a few minutes of arc, but sometimes there might be random movements over perhaps 10 or 20 min of arc, although in each case the person would be trying his best. If a person were at all nervous in a job it could be imagined that he might get into a state of mental "flutter", and if training gave confidence to a subject in the task he was doing, his mental discrimination would thereby be improved.

Summarizing, he felt quite sure that training and mental factors formed an important part of the ability to carry out visual tasks, but nevertheless there were certain optical and physiological limits to what could be discriminated. Of course, in the case of tasks involving both hand and eye, training and practice obviously contributed a great deal to improving the co-ordination between the two.

Dr. Pringle asked, with regard to traffic lights, whether the position of the light gave some indication? If a person was unable to distinguish the red, orange and green he could at least see from what part the light was coming.

The second point was under what type of illumination was one looking at a colour? Women invariably went outside a shop in daylight in order to match colours, instead of doing it under artificial light. However, in an automatic telephone exchange, for example, there might be a range of 350 shades of cable and he had never yet known anybody connect up a wrong one.

Prof. Wright, in reply, said that undoubtedly where it was possible to provide position or shape as an additional clue to colour it was a good thing to do, because every clue possible should be given to colour defectives. As regards lighting, in general the higher the level of illumination the better would be colour discrimination, so that colour defectives who had poor colour discrimination could effect a slight improvement with a raised level of lighting.

As far as the quality of the lighting was concerned, tungsten lighting would be bad for trying to distinguish, say, blues from blacks because there was much less blue energy in the light from tungsten compared with daylight, whereas when discriminating between red and orange one would not be very much better off in daylight than in tungsten light. On the whole ladies were wise to do their colour matching in daylight. The lighting would make little difference if the two materials had been dyed with the same dyes and had the same spectral absorption but, if by any chance the dyes were different, one might get a match in tungsten light and not in daylight or vice versa.

With regard to colour defectives and coloured cables, considerable confusion was possible and Dr. Pringle had been extremely fortunate in never having had a case where the cables were coupled up incorrectly. Some years ago he had had some correspondence on the importance of colour vision in different industries and, among others, he had been in touch with a firm concerned with electrical wiring. Experiments on the type of mistakes made by one of their colour-defective workmen showed that about twenty different pairs of cables might be wrongly connected. Sometimes, of course, the sleeving had a pattern as well as a colour, but if he was in doubt the man concerned, who was conscientious, would get somebody else to help him. It had to be remembered that in that type of operation the colours were sometimes judged in good illumination, but sometimes the cables were dirty or the illumination was anything but good.

Dr. Tideswell asked the lecturer if he could give a little more information about the time factor in perspective.

Prof. Wright replied that undoubtedly if one had a certain time to make a judgment one was more likely to get it right. On the other hand, he did not want to exaggerate the importance of having plenty of time because one of the amazing things about the eye was how quickly one could see and interpret a scene. He wondered whether Dr. Tideswell had anything specific in mind.

Dr. TIDESWELL said he had in mind the problem of driving in mist and in trying to decide when or what was the object in front, if it was!

Prof. WRIGHT, in reply, said in that case it did take a finite time to see, but he thought the time factor there was not really so much what was going on in the eye as what was going on in the brain and the interpretation of the light pattern. For example, work had been done on three-dimensional vision and 3–D pictures to determine the contribution to depth and distance given by monocular clues such as size, perspective, overlay, light and shade, and parallax. Two pictures could sometimes be so arranged that the binocular clues gave a certain three-dimensional effect, while some of the monocular clues apparently gave the reverse information. It might then take half a minute or more before the brain had sorted out the different clues and decided what answer would satisfy them all.

When driving in a mist the normal clues were changed by reduced contrast, reduced sharpness, less light, and so on, and because of this the brain required a longer time to interpret the pattern.

Dr. PIPER asked how the eye interpreted black, white and the greys, as well as the hues which Prof. WRIGHT had already mentioned.

Prof. WRIGHT, in reply, said one got white and grey when all three receptors were acting together and more or less in equal proportions. If the overall activity was reduced by cutting down the light the sensation of brightness diminished and one tended to go from whiteness to grey, but whether one would see a certain area of light as a grey or white would depend very much on the surrounding conditions. If there was an illuminated white surface in a completely black field it would look white; if, however, one suddenly switched on a much brighter surround field it would immediately change to grey or perhaps to black because of the contrast between the two. The subjective appearance was determined very much in relation to other colours in the scene.

Mr. H. HASEL (London County Council), referring to the subject of dark adaptation, asked whether there was anything to be gained by going from 1000 to 2 lm/ft^2 in gradual logarithmic steps.

Prof. WRIGHT, in reply, said that if one went suddenly from 1000 to 2 lm/ft^2 an object illuminated at 2 lm/ft^2 would appear very faint and one would have to wait a certain time, say 1 or 2 min, before becoming fully adapted to the lower illumination level. If, however, the illumination were lowered in logarithmic steps, then undoubtedly this would provide a more uniform gradation and adjustment to the change in light level.

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SUBJECTIVE ASPECTS OF THE EVALUATION OF LIGHTING*

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Abstract—There is now available information on the effect of lighting levels on visual acuity and visual performance and of the effect of the brightness relations in the field of view on visual comfort. Much remains to be done before we can confidently design the ideal lighting installation, but nevertheless we know quite enough now to assess on their merits those factors which assist in the provision of good lighting. Each factor must be given its proper significance in the assessment of the lighting installation as a whole. As with many other problems of design, compromises have to be decided between opposing factors. Perhaps the most difficult compromise is that necessary to achieve a balance between high levels of illumination for good visual performance, and satisfactory brightness relationships in the field of view to ensure absence of discomfort.

INTRODUCTION

IT is useful to follow the development of lighting thought and lighting practice over the last 50 years. The pendulum has swung first one way and then the other in response to the introduction of new lighting methods. Fifty years ago artificial light was expensive and could only be provided in small quantities. But the eyes demanded a certain minimum level of illumination to perform their function satisfactorily. It was therefore necessary to direct the small quantity of expensive light on to the work and the work alone. So a tradition of local lighting grew up around which all lighting techniques were developed. For some years purely local lighting was the only method of artificial lighting which could be practised in any but the most opulent surroundings. It is interesting that this form of lighting was not only expedient but was also considered to be good. Relatively few people demanded high levels of general lighting once darkness had descended. In some circles this tradition still persists. Many elderly people, and not only elderly people, are still convinced that local artificial lighting alone is more comfortable, gives better vision than more modern forms of general lighting.

The introduction of the cheap tungsten filament lamp together with a determined attempt on the part of the electrical supply industry to sell electric current cheaply and in large quantities, brought about the first major change in lighting thought and lighting practice. For the first time people had the opportunity of seeing what could be done by artificial lighting methods which took as their ideal the high levels of uniformly distributed light which were available from natural lighting. On the whole people received this revolution with satisfaction. Before very long general lighting was the rule rather than the exception in workshops, offices and schools. In the home local lighting prevailed much longer, but the introduction of cheap ranges of low wattage lamps coupled with the popularization of the two-part tariffs in England, enabling current for lighting to be obtained very cheaply, eventually persuaded the householder that he too could try to emulate daylight after darkness had fallen.

The introduction of the fluorescent lamp with its higher luminous efficiency led to the realization in practice of the ideals of high illumination levels which had been advocated for many years from the laboratory. In America, particularly, general lighting to give levels of illumination up to and above 50 lm/ft^2 was developed and pushed ahead with vigour. But soon it was apparent that in some ways the wagon was off the rails. HARRISON (1937) pointed this out in his now classic paper "What is wrong with our 50 ft candle installations?" which appeared just before the Second World War. What was wrong, said Dr. HARRISON, was that lighting engineers, in pushing up the illumination levels to the values recommended by the laboratories, had not realized that lighting techniques designed for low levels of general lighting were not in fact applicable to high levels. Everything does not go up in proportion. As the illumination level is raised with existing techniques, so the observer becomes conscious of excessive glare discomfort, due to the view of too many bright sources of light directly in the field of view. It is important to note that he rarely complains of "glare", he usually says there is "too much light". Fortunately Dr. HARRISON was able to recognize that this complaint of "too much light" was not in fact related to an excessively high level of illumination on the work, but was a factor associated with the pattern of brightness in the field of view.

The work which was subsequently undertaken in America, in Great Britain, in Holland and more recently in Germany, is leading to a swing of the pendulum back to local lighting, but with the important exception that the surroundings are no longer left in darkness and gloom as they had to be for economic reasons 50 years ago. Local lighting in fact acts as a supplement to an adequate level of general lighting. Lighting technique is at a stage of development comparable with that which took place when the cheap filament lamp was first introduced. It is a development which can only be realized successfully if those responsible for lighting research and those responsible for lighting practice work closely together with understanding and co-operation.

LIGHTING AND THE VISUAL TASK

It is very easy to demonstrate that the more light we have on the work, the better we are able to see. It is most likely, but it does not necessarily follow, that because we can see better we will perform better visually. In addition to the effect of illumination levels on visual acuity, it is necessary to find the effect on visual performance, i.e. the ability of the subject to perform a visual task under the conditions of which he is going to work. That is the basis of the research work undertaken by WESTON (1943) following on an idea of BEUTTELL (1934), and which now forms the basis of the I.E.S. Code of Lighting Practice in Great Britain. WESTON took a visual task designed to take into account the most important factors of visual performance. Observers working under laboratory conditions were asked to make the observations, and in this way WESTON round the relationship between illumination levels, contrast, size of visual task and the visual performance given by the observer. This "visual performance" was something different from the visual acuity investigated by, for example, the Snellen chart method. It measured not only the observer's ability to do a visual task but also his actual performance under the conditions which were presented to him. It was one stage farther on the road.

However, because an observer can perform efficiently, it does not follow that he is performing easily. He may be able to summon his last resources to perform WESTON's

visual performance test when it is very difficult, but he may not be able to do it without considerable expenditure of effort. WESTON believes that this factor should manifest itself in speed and in lack of accuracy of the performance by the subject. But another way of estimating the ease of seeing is to ask the observer to judge it himself. At the Building Research Station we have for some years used a special psychological technique which we call the "multiple criterion technique", which enables us to assess these subjective factors to a greater order of reliability than hitherto, and, what is more, we find how the relevant physical variables affect the sensation of, for example, degree of difficulty. Using this technique it has been possible to find the relation between the level of illumination and the ease of performance under various conditions, such as, for example, reading standard "Times Roman" letters under practical conditions. In this way we know the effect of illumination level on ease of seeing, as well as on visual acuity and visual performance as determined by WESTON's work and the work that went earlier.

Here then is the solution to the first of the problems confronting the lighting engineer in his attempt to evaluate the whole effect of lighting. He can demonstrate clearly that the more light he has on the work, the better will be the worker's visual acuity, his visual performance, and the ease with which he performs. If the lighting is initially bad, a great improvement in vision will result from making it moderate. But if the lighting is initially moderate, a vast amount of more light is necessary to make it good; the law of diminishing returns operates very typically. This is a very difficult situation to explain to the non-technical executive. The business man and his accountant naturally think arithmetically, but the lighting engineer has to think logarithmically.

GLARE OR "TOO MUCH LIGHT" AND THE LIKE

We once did a simple experiment at the Building Research Station merely as a demonstration to illustrate some of our more complicated researches. It is common practice to light small offices with opal spheres, a practice which we now deprecate, of course, but is still not uncommon. In a small office, the opal spheres were lamped with 500 W photo-flood lamps controlled by variable transformers. In this way it was possible to vary the illumination in the office from a very low level to a very high level indeed without any change in the method of lighting technique (the colour temperature of the light sources did of course change). The observers in the experiment were given a simple visual task to do, which consisted of reading some rather poor print. At low levels of illumination their chief complaint was that there was insufficient light to see the task. At a level of about 1 lm/ft^2 the task could be seen only fairly, while at 3 lm/ft^2 there appeared to be enough light to see moderately well. At this level of illumination no discomfort was experienced from the glare sources, which then had a brightness of about 300 ft lamberts. An appreciable improvement in visual ability appeared to result by continuing to raise the illumination level up to about 10 lm/ft^2, but at this level complaints about the glare discomfort began to be made. The glare sources then had a luminance of about 1000 ft lamberts. When the illumination level was raised still further, from 10 to 20 lm/ft^2, there was a noticeable increase in the glare discomfort which was not matched by an appreciable improvement in the visual ability. With still higher levels of illumination the discomfort became intolerable, and the lighting installation was quite obviously unsatisfactory.

Under the conditions of this very simple experiment, therefore, the optimum compromise between the amount of light necessary for good visual performance and the limitation on the brightness for absence of glare discomfort appears to be somewhere of the order of 8 to 12 lm/ft^2 which comes from light sources with a luminance of the order of 800 to 1200 ft lamberts.

This is a very simple experiment and with it we have obtained the compromise between two opposing lighting factors by direct appraisal. But of course in practice there are often a large number of variables to be considered all of which may be dependent on, or independent of, one another.

When lighting engineers began to prescribe higher and higher levels of illumination, they failed to realize, as HARRISON pointed out in his paper, that higher levels of illumination called for new techniques. In England in schools and in Government offices, installations provided to give high levels of illumination were found in practice to be the source of complaints usually expressed in the form of "there is too much light in here". Some of the lights were in fact switched out to produce a more comfortable installation. But in fact the complaint was really not of "too much light" but of "glare".

THE EVALUATION OF GLARE

Glare manifests itself in two distinct ways. There is the glare which reduces the ability to see ("disability glare") and there is the glare which causes discomfort ("discomfort glare"). In most interior lighting installations disability glare is of relatively small importance. The discomfort caused by glare, however, is of much greater current significance owing to the higher levels of illumination which are nowadays becoming general. Such discomfort is caused by the fact that the eye is unable to adjust itself simultaneously to luminances of widely differing values. The range of brightness which the eye can see comfortably at any one time is of the order of 1000 to 1, but the higher the level of brightness to which the eye is adapted, the narrower is this comfortable range (Fig. 1). This is illustrated by one or two quite simple examples. For example, in moonlight, although the adaptation level may be very low, perhaps 0·001 ft lambert, the eye can nevertheless look at the moon without experiencing a great deal of discomfort even though the luminance of the moon is of the order of 1000 ft lamberts. When the eye is adapted to normal daylight level, that is to say about 1000 ft lamberts, the brightness of a big white cloud, which may be between 1500 and 6000 ft lamberts, is to many people very uncomfortable; to most people the brightness of a white concrete road in full sunlight is distinctly unpleasant. Yet the white cloud and the white concrete road are only about 5 to 10 times the value of the average brightness to which the eye is adapted. People who have experienced the high brightness of a field of bright snow under full sunlight will know how acutely uncomfortable it can be, and yet in this case the white snow is probably only $1\frac{1}{2}$ to 2 times the brightness of the average field of view. This restriction of the comfortable range of brightness as the levels of adaptation are increased is the dominant factor in illuminating engineering today. When we were content with ambient brightnesses of the order of 1 ft lambert, the upper limit of comfort for the eye was something fairly remote, but nowadays we are demanding, on the grounds of increased visual performance, brightnesses of the order of 30–300 ft lamberts, and under these conditions the upper comfortable limit of brightness is something which is nowhere so remote from the average brightness of the field of view. In addition,

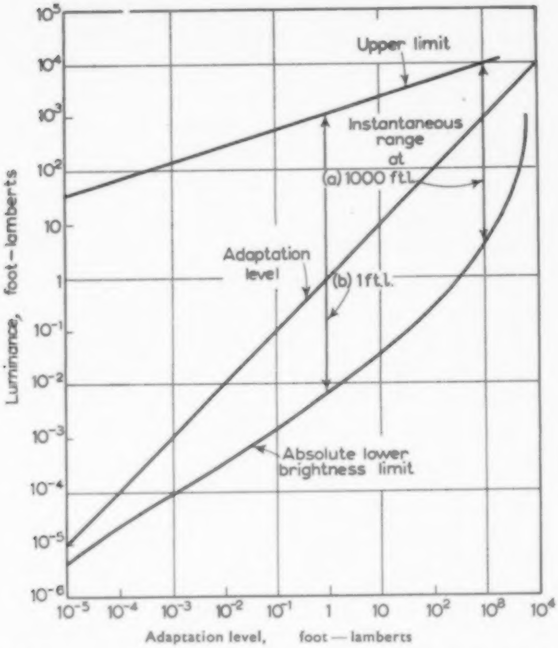

FIG. 1. Instantaneous visual range related to adaptation level.

these higher levels of brightness are being produced by many more lighting units than were previously necessary, and, since discomfort depends not only on the brightness of the glare source but also on its area, the risk of discomfort from glare is even greater.

Investigations in many countries have demonstrated conclusively that the discomfort effect due to glare can be assessed in terms of the brightness of the glare source, the apparent size of the glare source, its position in the field of view, and in addition to all of this, the brightness of the general surroundings in the field of view and the brightness of the immediate surroundings to the glare source. The glare discomfort effect can be expressed, to a reasonable degree of approximation, by the following formula:

$$G = \frac{B^2 A}{F}, \text{ or more precisely, by } G = \frac{B^{1\cdot 6} A^{0\cdot 8}}{F}$$

where B is the brightness of the source, expressed in ft lamberts, A is the apparent area of the source, expressed in steradians, F is the general brightness of the field of view, expressed in ft lamberts, and G is the constant depending on the degree of discomfort experienced.

The second formula fits the experimental data better, but the first has a great many conveniences in practical calculations, and may be sufficiently close for a first approximation.

The particular contribution which the British studies have made to this problem results from the use of a psychological method known as the "multiple criterion

technique". By means of this method the changes in the sensation of glare discomfort which result from changes in the physical constants outlined above have been determined. This means that we have learned something additional to the American "borderline between comfort and discomfort" (BCD), because we now know exactly what changes in the brightness of the light sources occasions a change in glare discomfort from "uncomfortable" to "intolerable" and so on.

It has also been possible to compare the results of these British investigations with investigations in other countries. The result of a great deal of work recently completed at the Building Research Station shows clearly the following conclusions:

(1) The differences between the various "glare formulae" are less than the differences in glare assessment made consistently by different observers on different occasions.

(2) The variability in the results is such that little could be gained by searching any further for the differences between the American and the European work without a very large number of observers, at least 500.

For these reasons the proposal was made from the British delegation at the International Committee on Illumination meeting in Zurich in 1955, that a compromise between the results of the most recent investigations should be adopted as an international glare formula of the form shown above. Since then a Working Committee has been appointed by the C.I.E. to undertake this task, and it has every hope of success.

Values of glare factor obtained from the proposed formula given above must be interpreted in terms of the criteria of glare discomfort as appraised by the general population. It has been found convenient to perform this in two steps, relating the glare factors first to the glare assessment of trained experienced observers, and then to the general population. The first step has been effected in terms of the multiple criterion glare scales used by the team of experienced observers in the original British investigations. The glare factors appropriate to the different sensations of glare discomfort are given in Table 1.

TABLE 1. VALUES OF GLARE FACTOR G FOR FOUR CRITERIA OF GLARE

Glare criteria	Value of G	
	$G=B^2A/F$	$G=B^{1\cdot6}A^{0\cdot8}/F$
A (just intolerable)	3000	600
B (just uncomfortable)	600	150
C (just acceptable)	120	35
D (just perceptible)	24	8

These assessments are not, however, necessarily the same as those given by the average of the general population under the same conditions. Evidence has been obtained that subjects drawn at random from the general population are not as sensitive to glare discomfort as are people with experience in making such glare judgment. Fig. 2 shows the glare discomfort assessment of an "inexperienced" and

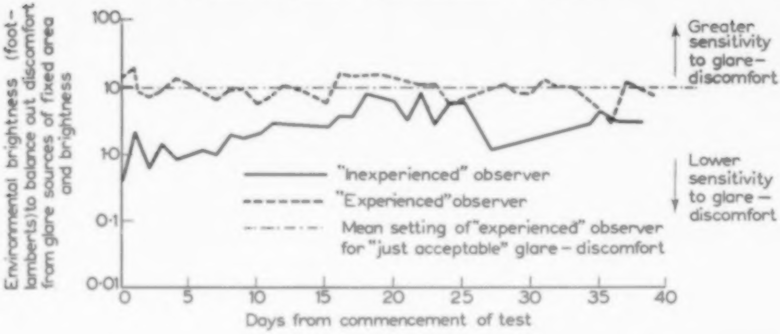

FIG. 2. Glare-discomfort assessments of an "inexperienced" and an "experienced" observer under identical conditions over periods of about 40 days for "just acceptable" criterion, showing increasing sensitivity of "inexperienced" observer to glare discomfort over the period.

an "experienced" observer under identical conditions over periods of about 40 days, showing the increasing sensitivity of the "inexperienced" observer to glare discomfort over the period. Studies were made with a large sample (50 observers) of people who could reasonably be taken to be completely inexperienced in matters of lighting and glare. Judgments were taken from all these observers under carefully controlled conditions, covering a suitable range of the physical variables. The results were analysed and a typical series is shown in Fig. 3. Fig 3. applies to one set of conditions, and shows the probability of the general population experiencing that particular degree of glare (here "just acceptable") in terms of the value of the background luminance.

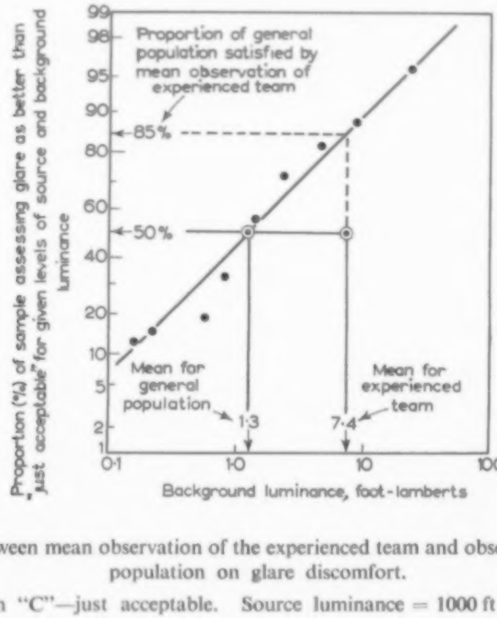

FIG. 3. Relation between mean observation of the experienced team and observations of the general population on glare discomfort.

Criterion "C"—just acceptable. Source luminance = 1000 ft lamberts.

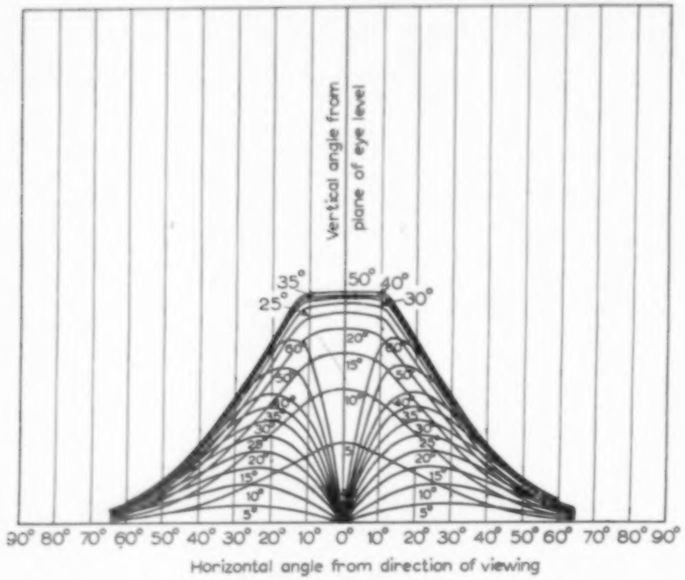

FIG. 4. Droop lines corresponding to semi-sinusoidal projection modified to allow for effect of glare source position.

It can be seen that the average of the general population is prepared to accept a background luminance of 1·3 ft lamberts whereas the average of the experienced team requires 7·4 ft lamberts in order to balance out the glare discomfort from the

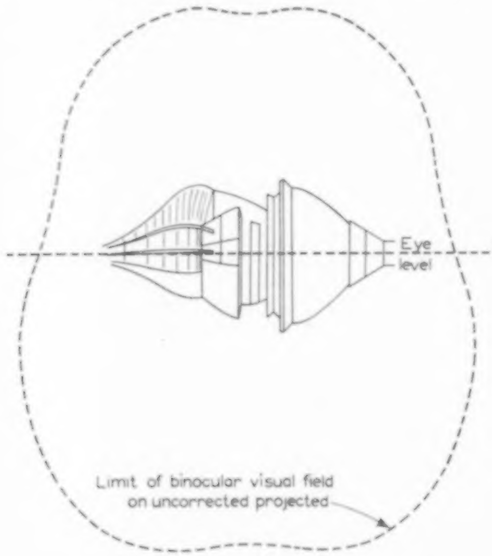

FIG. 6. Office interior plotted on semi-sinusoidal projection in which corrections have been applied to allow for influence of source position on glare discomfort.

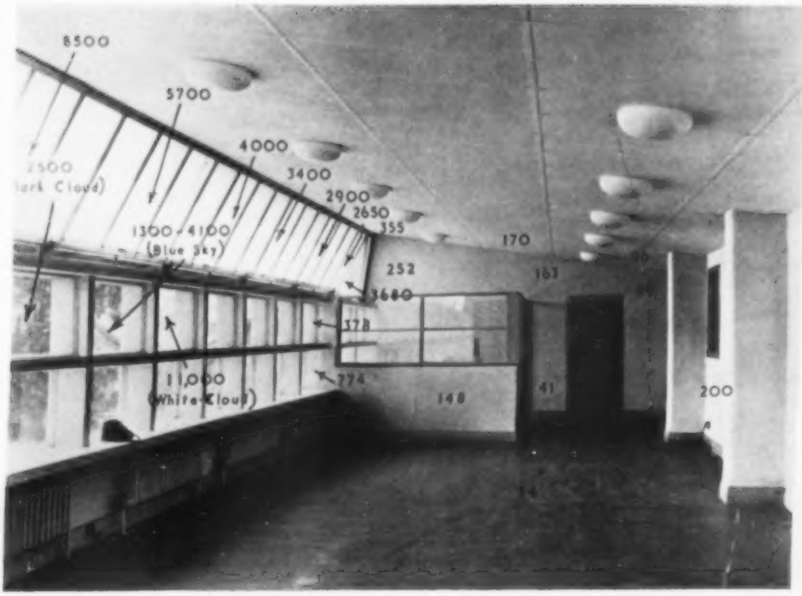

FIG. 5. Office with brightness measurements for glare assessments.

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given light source for the same degree of glare discomfort. At this latter level (7·4 ft lamberts) 85 per cent of the general population would be satisfied.

This figure is fairly typical for all the conditions examined. The conditions which would satisfy 50 per cent of the experienced people are found to satisfy between 80 per cent and 90 per cent of the inexperienced people.

It was therefore suggested to the C.I.E. that this basis (85 per cent of the general population satisfied) should be taken for a set of international glare tables.

Some difficulties may arise in substituting in the proposed glare formula, especially under conditions such as daylight or luminous ceilings, in determining the value of the term A for the apparent size of the source. A special equal-area plotting web (Fig. 4) has been devised in which the "position index" (i.e. the compensation for the angle between the direction of viewing and the direction of the glaring source) is introduced in the diagram. A room can therefore be measured up and plotted on the diagram as shown in Figs. 5 and 6. The glare sources plotted on this diagram are measured with a planimeter and this value substituted in the glare formula.

THE EVALUATION OF LIGHTING

As a result of all this recent work the lighting engineer now has at his disposal methods for evaluating the effect of illumination levels on visual ability, and the effect of the brightness of the environment on visual comfort. He still lacks, however, some fully scientific method for evaluating the general effect of the installation as a whole. This is a difficulty which we are always having to face when we are concerned with Gestalt properties. Most experienced lighting engineers or architects are capable of summing up the general impression of a lighting installation and of grading it as "good" or "bad" or any other general assessment which seems appropriate. Usually, or at least quite often, a consensus of opinion agrees in this assessment. On the other hand, it is the most difficult thing to find some physical measure of this "goodness". Our usual procedure when we are faced with a Gestalt situation is to take the situation to pieces, for example, into visual performances, visual comfort and so on, make measurements on each of the component factors, and then attempt to add these assessments together, weighting each factor suitably, and so arriving at a final assessment of the whole situation. This technique works when we know exactly the significance of each of the factors. Usually, however, we do not, and so the weighted sum may give quite a misleading assessment of the Gestalt.

The difficulty is that in the process of the mental assessment of the lighting installation there is a continuous process of trial and error, of compromise and compensation, and these processes depend upon the various physical factors. For example, in an installation which has a fairly high level of illumination, and only a moderate degree of glare, the weighting for each of these factors may possibly be about the same, whereas if there is a very high degree of glare, the weighting for glare may have to be proportionately greater, because glare is then an obtrusive sensation, and not one which has to be searched for. It has been suggested that some methods of factorial analysis may yield the satisfactory solution to this problem of the integration of the various physical factors which determine the "goodness" of a lighting installation. There seems some doubt, however, if such a study would be either successful or worth while. In practice it is often much more useful to know the component characteristics of an installation when one is judging its merits for a particular purpose.

CONCLUSION

The evaluation of lighting must take subjective factors into account. As has been shown in the paper, techniques are now available for the assessment of many of the most important of these factors. Some doubt exists, however, as to whether it is worth while trying to integrate all these assessments into a single figure of "goodness".

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DISCUSSION

Dr. Hickish paid a tribute to the practical value of the paper and suggested that many of the problems which arose were not entirely due to the engineers but also partly to the architects. He cited the case of a very modern factory which had been provided with an 8 ft ceiling in the office where the illumination was by fluorescent tubes recessed into the ceiling so that the face of the fitting was flush with the ceiling. From the moment that office was occupied there were complaints of discomfort. Removal of one of the tubes from the twin tube fitting reduced the brightness ratio between the fittings and the surrounding ceiling, but it was still within the range which Dr. Hopkinson's work had suggested would cause discomfort; this was at present being remedied by increasing the illumination on the ceiling itself. It was undoubtedly a case where the architectural design had led the designer of the lighting installation into error.

Dr. A. R. McGibbon (British Railways) said he was sorry that Dr. Hopkinson had criticized their only weapon, the photometer, and now they could not even use that he would like to ask whether the lecturer felt there was some variation between various people in their sensitivity to glare. He was not normally glare conscious but in that particular lecture theatre he was troubled by a light in front because its brightness was far in excess of that very low figure which Dr. Hopkinson had given of 3 cd/in². The Factory Act allowed one to go to 10 cd/in.², but he was apparently suggesting 3 as the limit.

Dr. Hopkinson, in reply, said that undoubtedly people did vary in their sensitivity to glare. Observations had been taken from a large number of observers and the distribution of sensitivity over the general population had been found and had been related to the more detailed judgments which had been made in the laboratory.

He had not of course wished to convey that the photometer was no longer of any use in assessing lighting. There were the two factors which were important: the amount of light, which the photometer measured, and then there was the discomfort effect which the photometer did not measure.

As regards the upper limit of comfortable lighting the Factories Act value of 10 cd/in² was based solely on experience, and had been set before detailed research had been completed.

Another point was that, in a factory, generally speaking the light sources were so much above the general line of sight as compared with their position in an office or a schoolroom that one could tolerate a higher level of brightness and yet enjoy relative freedom from discomfort. Also most people who were busy in a factory were prepared to put up with rather more discomfort than they would in, say, a private office where they would have time to sit around and complain about the situation.

In answer to Dr. McGibbon's other point, if one measured the proportion of people who were sensitive to a given level of glare, say, "just acceptable", it was found that there was a wide variation. Undoubtedly some people had a visual make-up which made them more sensitive to glare than others, but also he believed that it was a matter of interpretation, that some people would complain about a degree of glare that would not worry others. There was a combination of visual and psychological factors which went to make up that very wide range, so it had been decided to design to meet the needs of 85 per cent of the general population.

Mr. W. H. Walton (National Coal Board) asked whether glare was influenced by colour. Was it

possible, say, to saturate one colour receptor by a very bright source but still leave the others functioning?

Dr. HOPKINSON, in reply, said it might be, but it had not been investigated. The only thing which had been investigated was the relative degree of glare which was given by different commonly-used light sources, such as sodium vapour or mercury vapour lamps for street lighting. He felt sure Prof. WRIGHT would know very much more about it.

Prof. W. D. WRIGHT said that on the whole it was not possible to stimulate one receptor and not the others, with the possible exception that if one illuminated the eye with light from the far red end of the spectrum, the green and the blue were not very receptive, but he believed it was true to say that any light would decompose the basic photochemical substance in the retina and one could not really hope to take one receptor out almost completely and leave the others operating. All would be affected, but some more than others.

The Chairman asked whether one might lose acuity by using colours instead of white, which would actually put one in a worse position.

Prof. WRIGHT replied that actually acuity improved a little with monochromatic light, but not as much as one would expect.

Mr. W. H. WALTON said he had really been thinking of the motor car headlamp problem, where one could see at low levels of illumination but it would still give a little help to the man coming in the opposite direction.

Prof. WRIGHT said that a large part of the motor car headlamp problem was due to scattered light in the eye, and that would operate, whatever coloured light was being used.

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VISUAL FATIGUE AND ITS MEASUREMENT*

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Abstract—The meaning of visual fatigue to the lighting engineer, concerned with the design of a lighting system which enables those working under it to operate at the highest efficiency for the longest time and with the minimum of strain, is discussed.

One technique put forward for testing visual fatigue by recording increasing error in a visual test is fully described, and an investigation to determine its suitability as a practical test is described. Reasons for the failure of this method to prove itself practicable are discussed, and the design and construction of an apparatus for studying a more objective method of measurement of fatigue by timing the accommodation process are described.

INTRODUCTION

IN speaking about visual fatigue we are speaking about something which has no precise and unique definition. Visual fatigue means different things to those concerned with different aspects of vision, and it is therefore necessary to define at the outset what will be meant by visual fatigue in the following discussion.

When we undertake a visual task, for instance, reading or close inspection, the eye is directed to bring the most critical part of the task to be imaged on the part of the retina with the highest power of discrimination. This direction is performed partly by the muscles of the head and trunk which perform the coarse movement necessary, and partly by the extrinsic oculomotor muscles which perform the fine adjustment of movement. The direction may be fixed as in watching a meter or small display, or it may involve more or less continuous motion as in scanning a printed page. Inside the eye, other muscles will be at work focussing the lens to produce the sharpest possible image, and adjusting the pupil in an attempt to keep the amount of light falling on the retina within comfortable limits. When the light finally falls on the retina, complicated chemical and electrical activities take place in what is a specialized extension of the central nervous system, and the coded visual information is transmitted to the cerebral certrex, where it is collated and interpreted.

The task of the lighting engineer is to see that each one of the functions of the visual apparatus and mechanism can operate at or near its maximum efficiency, and if the human being operated as a simple—or not so simple—machine, this task would be relatively easy to specify. Performance of the human machine could be measured, and the output related to variations in lighting quantity and quality. Unfortunately, however, the actual performance of a human being in a real task depends on many factors over and above the ease with which it can be done, the most important of these probably being the motivational factors. Thus, while it is quite possible to demonstrate improvements in specific visual functions such as acuity and speed of vision with such changes in stimulus as increase in illumination and contrast, practically no

difference in performance can be demonstrated (at any rate over periods of the order of some hours' work) as a result of very large changes in quality or comfort of the visual environment.

That quality and comfort of lighting do however have an important effect on the human being is a common subjective experience: we all know what fatigue and tiredness are, and how they can occur without physical effort, and we are aware that in some way a performance maintained under bad lighting is being maintained at some cost to the individual. It is this cost therefore of which we are trying to establish some relative objective measure in our studies on visual fatigue.

In considering the source of our subjective feelings of fatigue we can distinguish between muscular fatigue due to excessive activity or excessively long periods of contraction of certain sets of muscles, and the feeling of general or central fatigue or tiredness due to the difficulty of the task.

Weston (1953) has clearly differentiated these two forms of fatigue, and described in some detail the operation of the various sets of muscles involved in a visual task. He has also discussed whether the retina itself can show any sort of fatigue effect, and has concluded that whether or not this is possible, it is certainly impossible that any sensation other than that of light can be experienced in the retina itself.

The avoidance of muscular fatigue is a fairly straightforward problem for the lighting engineer. The important thing is to ensure that a comfortable posture and focussing distance are not hindered by shadowing, lack of illumination or disturbing bright reflections, and that a comfortable background is provided on which occasional relaxation of accommodation can take place.

However, even if these conditions, which might be termed the mechanical ones, are satisfied, there still remains a distinction between the tiredness caused by poor lighting, where the visibility of the task is not satisfactory or there are distractions or other undesirable features about the brightness pattern in the field of view, and the maintenance of alertness and ability to concentrate resulting from lighting where all these features have been made as good as possible. It must be concluded that these parts of the cost to the individual of undertaking a prolonged task, whether they arise in the retina or in the higher centres, have their eventual effect on the central nervous system and that it is at the functions directly influenced by this that we should look with the greatest hope of finding some effects which would enable us to compare the costs of tasks undertaken under different conditions. These effects are perhaps not properly called visual fatigue, but (as they have been called by Mackworth) "fatigue visually occasioned".

In a search for methods of obtaining some indication of the state of the central nervous system as affected by the visual stimulus, various workers have tried many different techniques. These include measurements of muscle action potentials (Travis *et al.*, 1951), critical flicker fusion frequency (Brozek and Keys, 1944; Grandjean and Battig, 1955), electro-optical sensitivity (Mita *et al.*, 1951), and accommodation reserve, but there is not space to discuss all these methods here; it is only sufficient to say that, while some workers have demonstrated successful results under certain conditions, there seemed to be insufficient encouragement for us to investigate in detail any of the methods which could readily be used with a small panel of inexperienced subjects.

SALDANHA METHOD

One method which appeared promising enough to be investigated in detail was that devised by SALDANHA (1955) at the Medical Research Council's Applied Psychology Unit at Cambridge, and this will be described at some length as the investigation illustrated many of the difficulties inherent in such techniques.

SALDANHA was principally interested in assessing the deterioration in performance of a visual task with prolongation of the time, and in order to reduce motivational effects he measured not the quantity of output but the accuracy of performance in quite a difficult visual task. This task was the setting of a fine vernier gauge reading to 0·001 in, the accuracy of setting of which could be read on a dial gauge reading to 0·0001 in, which was a greater accuracy than that to which the vernier could normally be set by the naked eye. (The apparatus was similar to that shown in Figs. 3–5.)

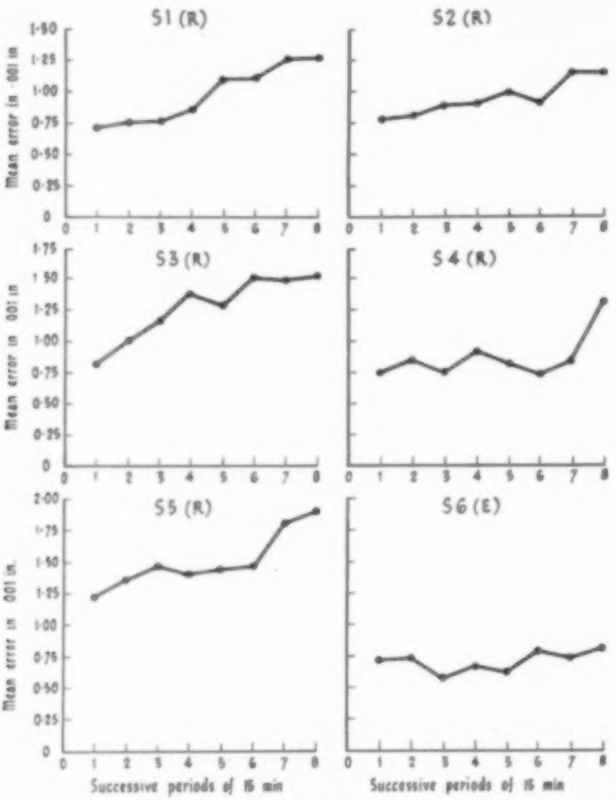

FIG. 1. Variation in error with time. (SALDANHA's experiment (1955). Individual subjects.)

SALDANHA's subjects were partly naval personnel who were originally untrained, partly engineering students and partly research workers. All were given some practice before the experiments, and the naval ratings were given a considerable amount of training. They were asked to set the gauge (by means of an easily turned handle) to settings which appeared on a strip of paper behind a window as accurately and quickly

as possible. The illumination on the vernier scale was set at approximately 5 ft candles. When the subject had set the gauge to his satisfaction, he pressed a key which triggered a camera making a photographic record of the number he had been asked to set, the reading of the dial gauge recording the actual setting made, and the time taken to make the setting as recorded on a chronometer. This having been done, the next dimension to be set automatically appeared at the window and the chronometer was reset to zero. The subject was told that both accuracy and speed would be recorded, and that he was to continue with the task until told to stop. The experiment continued for 2 hr at a stretch and the errors of each subject in thousandths of an inch between the setting given and that actually set were averaged over every 15 min period.

Not all subjects showed the same rate of increase in error with time, nor were the increases in error always positive from every quarter of an hour to the next, but, without exception, all eighteen of the subjects showed a greater average error during the eighth quarter of an hour than during the first, and the average errors of all subjects increased quite steadily during each of the eight quarters of an hour, with significant differences (at the 0·001 level) between the second and first quarters of an hour and between the last and the second quarters of an hour. Fig. 1 shows a typical set of individual results, and in Fig. 2 the broken line shows the average results for the eighteen subjects.

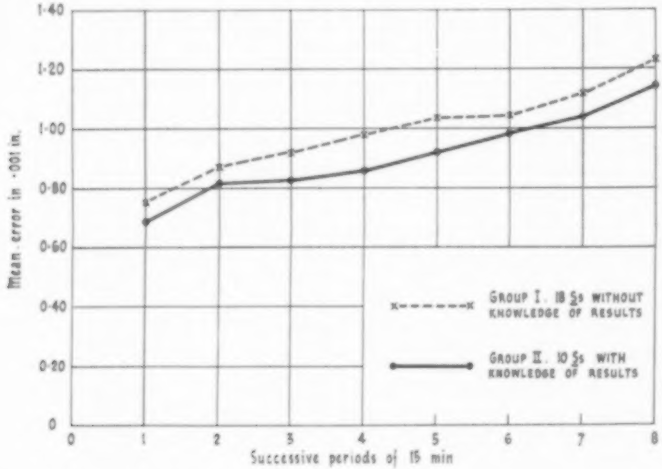

FIG. 2. Variation in error with time. (SALDANHA's experiment (1955).)

It is interesting in passing to note that in this experiment there was a tendency among the research workers and engineering students to increase their speed of setting during the second hour of the test as compared with the first hour, but there was no correlation between the speed with which a setting was made and its accuracy. It is also of interest to note that no differences in eye-muscle balance (by the Maddox Wing test) or visual acuity performance (as determined by the Weston Landolt Ring test) between the beginning and the end of the test period were detectable; although a certain amount of tiredness was complained of by most subjects.

APPLICATION OF SALDANHA METHOD TO LIGHTING RESEARCH

The clearly defined change in average error which appeared during the test period and its apparent relation to the "fatigue visually occasioned" seemed a good indication that this method might well be used as a basis of a test to show up differences in quality of lighting by the differences in amount of visual fatigue produced.

After discussion with Dr. Saldanha and Dr. Mackworth the head of the M.R.C. Applied Psychology Unit, a replica of Dr. Saldanha's apparatus was constructed at the Building Research Station, and a number of subjects were asked to carry out the test for the 2 hr period. The apparatus made at the station is illustrated in Figs. 3, 4 and 5. The surround to the visual task was made as light as possible with white card or white paint, in order to produce a visual pattern which should be found tiring.

In all, 11 subjects were tested, and 8 of these had sufficient training to be able to set initially to the required accuracy. The subjects were mainly chosen from staff associated with lighting research, with the addition of one computer and two trained mechanics.

The illumination level on the vernier scale was set at 14 lm/ft^2 for the first series of tests, and the average errors over quarter-hourly periods for the duration of the 2-hr run were plotted and examined for tendency of increase or decrease. It was found that a very slight increase over the whole 2 hr period did in fact occur in the average results of the first batch of eight subjects, but that individual results were very variable, as many subjects showing a decrease in error as showing an increase. In an attempt to obtain a more definite tendency, the tests were repeated under an illumination level of 1 lm/ft^2 with firstly the more consistently reading subjects from the first test, and secondly two trained mechanics. Again no consistent pattern of increase in error, or of increase in variance of error, was shown, and it was interesting to observe that the general level of accuracy of the trained mechanics was rather worse than that of the other research workers.

One other attempt to influence the performance of the subjects was made, and that was by applying a stress to the subject after the first half-hour by telling them that only settings with an error of not more than 0·0005 in. could be counted and telling them after each setting whether it would be accepted. In fact all errors for the three subjects tested in this way were eventually plotted and analysed, and these showed that, while one of the subjects showed a marked decrease in performance and increase in variance under this stress, one was not clearly affected at all, and the other only slightly.

A final attempt was made to check whether the apparatus or technique was in some way sufficiently different from that of Saldanha to account for the poor correspondence of our results with his. Our experimenter tested four of our trained subjects at the Applied Psychology Laboratory in Cambridge under Saldanha's direction and adopting carefully his full procedure. The results of this test were not very much different from those obtained at the station, and did not show much correspondence with the results previously obtained by Saldanha with his subjects.

The results of this investigation led to the conclusion that Saldanha's method did not appear suitable for use by non-psychologists, testing subjects who were bound to have some interest in the progress and result of the experiment. It was clearly shown that the nature of the test was not as purely objective as had been supposed, and that the psychological aspects, particularly those concerned with motivation and training, were important.

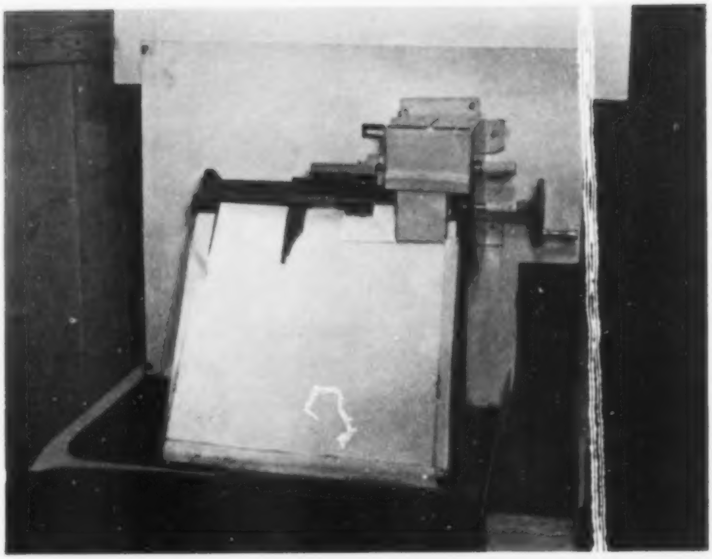

FIG. 3. Vernier setting apparatus.

FIG. 4. Vernier setting apparatus subject in position.

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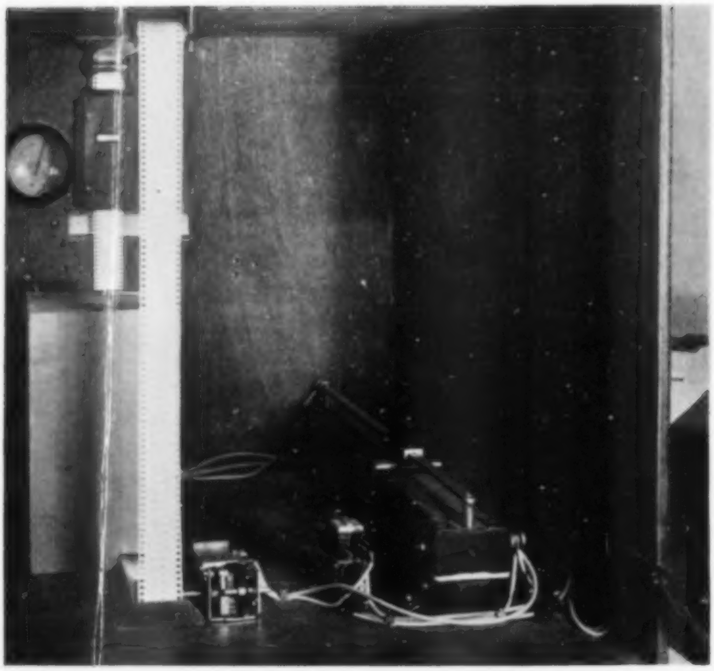

FIG. 5. Vernier setting apparatus. View from rear.

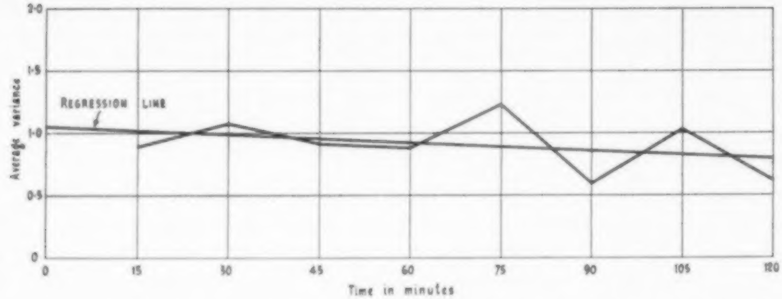

FIG. 6. Average variance of 6 runs by trained subjects. (Errors of 0·010 in. and below included. Illumination on plane of scale 14 ft-lamberts.) B.R.S. Vernier setting experiments.

The following features of SALDANHA's subject selection were thought to be significant in influencing their performance on the test:

(1) The subjects were selected to ensure that they gave consistent readings with high initial accuracy. This meant long periods of training (for half-an-hour a day for up to a week) for the unskilled subjects, but only training for an hour for the engineering undergraduates and research workers, and it is understood that this involved a high rate of rejection, certainly for the unskilled subjects.

(2) The naval ratings (and presumably the engineering undergraduates) were all men in the 18–23 age group, whereas our subjects were in the 25–40 age group, and were of both sexes. It was pointed out that no knowledge existed of sex correlations in performance of the task.

(3) The subjects had no concern whatsoever with the result of the experiment, whereas most of our subjects naturally approached the test from the point of view of a research worker in the same or allied fields.

In view of the fact that subjects for an investigation by the station involving tests for a long period of time could not readily be chosen from outside the research staff, and even then at a cost of interfering with their own work, the indications of this investigation were that a test should be sought which depended less on practice and training effects and less on a delicate psychological balance of motivation and objectivity.

MEASUREMENT OF ACCOMMODATION TIME

In further consideration of the more objective methods of indicating the effects of prolonged visual work, attention was drawn (particularly by LE GRAND in a private discussion in Paris) to the fact that more evidence had been put forward of the effects on accommodation and convergence. (The successful experiments described by F. V. MICHAL (1954) were also noted.)

In view of the fact that SALDANHA had not demonstrated any change in muscle balance during his experiments and in view of the slightly nebulous quantities represented by near and far points of visual accommodation, it was decided to study the possibility of obtaining an indication of fatigue imposed by a visual task by the change in time for the eye to accommodate from near to far vision.

Both objective (measurement of lens curvature) and subjective (measurement of time for sharp vision) techniques of measurement of accommodation time have been

well established, and it was decided to construct a development of the apparatus described by FERREE and RAND (1918) and later used by ROBERTSON (1936). In this, the targets at near and far distance are presented consecutively for measured lengths of time which can be decreased until the subject fails to recognize sharply the second target. FERREE and RAND exposed their targets by means of a pendulum shutter, but we have constructed an apparatus with a motor-driven shutter and a master shutter giving a single exposure, so that repeated presentations of the targets can be made in fairly quick succession. The assembled apparatus without its cover is shown in Figs. 7, 8 and 9. The continuously rotating sector disk has a mirrored sector and an adjustable clear sector. The targets are Landolt rings with a gap subtending about 3 min at the eye, printed on to two loops of 35 mm cine-positive film, and these loops are fed through an illuminated gate by a solenoid-operated sprocket which moves the film a distance equal to the standard cine frame spacing. The single exposure shutter mounted between the eye and the sector disk has a white painted blade which can be illuminated by 15 W lamps, so that the level of light adaptation remains roughly constant. Arrangements are made to insert a spectacle lens in front of the subject's eye to bring the near target apparently to the near point.

At the commencement of the experiment the subject is looking at the illuminated shutter closer than the near point. After the experimenter has pressed the control button, as the mirrored portion of the sector disk approaches the line of sight, the shutter opens and the targets simultaneously change. As the mirrored portion of the sector disk passes the line of sight, the near target is seen apparently at a distance of about the near point for a short time and it is then replaced for another period of time by the distant target which is optically placed at infinity (or beyond) by interposing a further lens system situated between the sector disk and the distant target, after which the outer shutter closes. The time for which the distant target is viewed can be adjusted independently of that for the near target by adjustment of the angle of clear portion of the sector disk, and the time of both exposures is varied by continuously variable gear fitted to the motor. The cycle of operation is governed by three cams mounted on the shaft of the sector disk which operate micro-switches and by two interconnected relays, which are arranged so that the cycle is not repeated until the control button is again depressed.

The Landolt ring targets were chosen to be of such a size that the position of the gaps could be easily seen at the slowest rotation time of the sector, and the subject is instructed to call out the position of the gap in both the near and the far rings. This ensures that the eye is adequately sharply focussed for the near target before changing to the distant one. The gaps are orientated at random in each of the six directions—12 o'clock, 2 o'clock, 4 o'clock, 6 o'clock, 8 o'clock and 10 o'clock, and the subject is instructed to identify the orientation by these block positions. There are 40 targets on one loop of film and 41 on the other, so that the complete sequence only repeats once in 1641 presentations. A sequence of up to 5 presentations is given at each speed of the sector disk, and if the orientation of the target gap is correctly called 3 times in succession or 3 times out of 5, the speed is increased by a predetermined step each time until it is incorrectly called 3 times out of 5. The time of exposure of the distant target in the previous sequence is then taken as the maximum speed at which the eye can accommodate from near to far distance.

This maximum speed of accommodation is measured for each subject before and

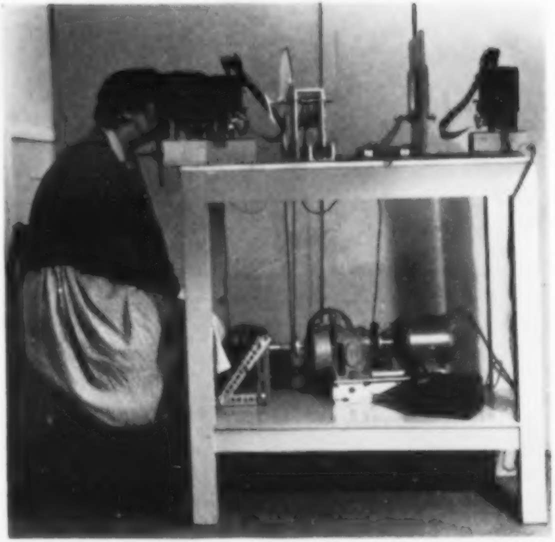

FIG. 7. Apparatus for measurement of accommodation time.
General view.

FIG. 8. Apparatus for measurement of accommodation time.
View from viewing end.

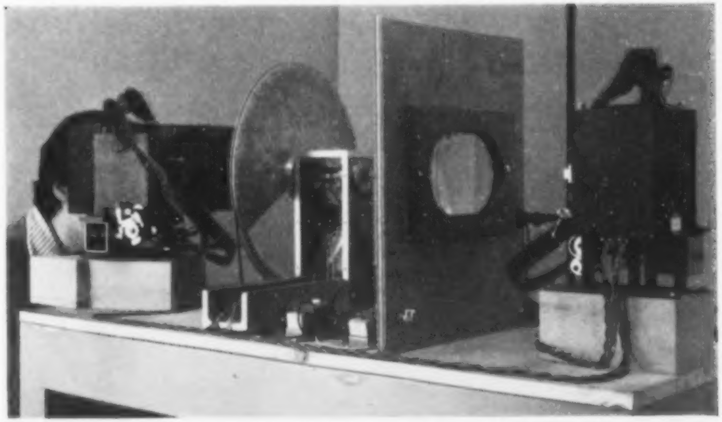

FIG. 9. Apparatus for measurement of accommodation time.
Looking towards viewing end.

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after a 2 hr spell of setting of the vernier as in the Saldanha method described above, and to avoid possible psychological problems arising from the use of subjects with an interest in the work, arrangements are being made to recruit and pay subjects from outside the station staff. It is hoped to report results in a future communication.

Acknowledgements—It is desired to acknowledge the co-operation and advice of Dr. MACKWORTH and his staff at the Applied Psychology Unit of the Medical Research Council.

The work described is being carried out as part of the research programme of the Building Research Board of the Department of Scientific and Industrial Research and this paper is published by permission of the Director of Building Research. The work is being done under the aegis of the Joint Committee on Lighting and Vision of the Medical Research Council and the Building Research Board.

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DISCUSSION

Mr. FLETCHER (Northampton College) said he was intensely interested to hear the results of the subjective work, largely because he was quite staggered to learn that any such method should be envisaged. For some years he had been taught, and indeed had been teaching, that there was no such thing as a fatigue of accommodation from near to far vision, and he was under the impression that FERREE and RAND's work in connexion with the apparatus mentioned had at least some pointers in that direction.

Secondly, when Mr. COLLINS was searching round for criteria of fatigue had he considered the matter of pain or discomfort as produced by the contraction of the iris, mostly the sphincter of the iris? It seemed to him, from experience of subjects with dilated pupils, that this was very important.

Mr. J. B. COLLINS, in reply, said he believed it was a fact that Ferree and Rand had not found any very significant change with fatigue, but he thought other workers had done so. Robertson had shown that the accommodation time varied with fatigue and Kirchhof had shown some increases after fatiguing the accommodation muscles; it was hoped to get some results in view of this work.

With regard to the pain on contraction of the iris muscles, he was not quite sure what the speaker meant.

Mr. FLETCHER said he felt that in glare or in any other impingement of light upon the eye there was a matter of an iris-pupil closure and that was one of the most prevalent sources of discomfort. A person screwed his eyes up but somehow he believed it was the iris which was at fault in giving the discomfort, and when the pupil was dilated—paralysed, as it were—then there was if anything less discomfort.

Mr. J. B. COLLINS replied that it was really a subjective effect.

Mr. FLETCHER pointed out that the pupil contraction could be objectively determined.

Mr. J. B. COLLINS, in reply, said a study had been made of the question of pupil contraction with regard to discomfort and there did not appear to be any relation between the discomfort and the size of pupil.

Mr. H. LOWE asked whether visual fatigue caused breakdown in the general field of vision.

Mr. J. B. COLLINS, in reply, said not the sort of visual fatigue which was being discussed. He was really interested in the sort of visual fatigue which was caused by working hard in not very good lighting, and not in the ultimate breakdown. The only effects really were tiredness and a feeling of strain.

Dr. LANGDON (Building Research Station) asked whether there was any reason to believe that the switching of accommodation was an equally fatiguing task. Was it possible to replace the task of vernier setting by, for instance, a task of reading Landolt rings, one or the other presented at different distances, as a fatigue-inducing task?

Mr. J. B. COLLINS, in reply, said it could easily be done but he thought it would be cheating. It would be rather doing something which would lead to the sort of fatigue which was going to be measured. It would be all right if one could relate that reading of Landolt rings to a particular visual task. Supposing one had an industrial task of watching boilers or gauges; that might then be related to the fatigue which one would get from observing Landolt rings at different distances, but that would not be strictly comparable with, say, a very fine task in a factory, such as assembly or precision machining at a fixed distance.

Dr. P. J. R. CHALLEN asked whether one was measuring visual fatigue or just mental irritation.

Mr. J. B. COLLINS, in reply, said he did not know; what he wanted to measure was something. If they could relate whatever it was they measured to the quality of the lighting then they would have got quite a long way ahead.

The Chairman expressed surprise that Mr. COLLINS had chosen that particular method of setting the vernier. It was a very specialized task and he would have thought it would be necessary to do some comparative tests to show that it was representative of tasks which had to be done with high precision. It seemed to be such a specialized operation that it might not be representative of all the range of tasks which had to be done with precision in industrial work. It would be very interesting, if there was a particular correlation with that procedure, to see if the same correlation obtained with some other task which was quite different.

He personally felt that the lighting of vernier scales was a very difficult thing to achieve because of the finish on the metal, and particularly on circular verniers.

Mr. J. B. COLLINS remarked that it was a very easy thing to do badly.

The Chairman said in his view that would again have made it a very undesirable yardstick because it would be difficult to become independent of the exact mode of illumination. It was undoubtedly a field in which a great deal more work was required.

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VISUAL TASKS AND VISUAL CAPACITIES—THEIR RATING AND MATING

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INTRODUCTION

VISION is becoming more widely recognized as being of great importance in industry. Blind people are capable of performing many occupational tasks, and automatic control is suitable for some processes. Vision remains a vital matter in the majority of industrial situations.

A task which conforms to a good standard of visibility can be performed accurately, quickly and safely. If the vision of the operator is inadequate the attributes of the task may count for nothing. Clearly, visual tasks and visual capacities must be matched to each other to avoid eyestrain, inefficiency and accidents.

Correcting spectacles are only one possible means by which vision can be improved. At present it is probably the most important, despite ten years of widespread use, of the National Health Service facilities. Almost half the adults in this country have spectacles of some sort. Careful surveys reveal that at least 20 per cent of those employed in industry today still need more adequate spectacle correction for work. In some cases no correction has ever been used, in others the correction is inadequate either in power or in form. Skill frequently compensates for visual difficulties in older people. In some cases spectacles are not required for close work despite low distance vision; the aptitude of the myope for such occupations as watchmaking is well known. Vision may have a good or bad effect upon working efficiency. In some cases work may have a bad effect on visual efficiency; especially is this true in excessively close work and in occupations where harmful radiation is found. In general, the more difficult a task is, the more care should be taken to ensure that it is carried out by someone with adequate vision. It is fitting here to mention the work of H. C. WESTON over the last 30 years and more, which has done so much to establish the relationship between visual performance and visual conditions. In America, M. LUCKIESH has been active in similar ways. At the Northampton College, London, where we train the majority of the nation's ophthalmic opticians, the subject of industrial ophthalmics has been stressed for many years.

COMPONENTS OF THE VISUAL TASK, AND MATCHING CAPACITIES

1. *Size*

In vision, the "size" of an object is best considered as the size of the angle which the object subtends at the eye; this is the same as the angle subtended by the retinal image of the object at the posterior nodal point of the optical system of the eye. The "visual angle" depends upon two factors:

(1) The dimensions of the object, called x, measured in centimetres.

(2) The distance of the object, considered rather as a nearness, in which case it is measured in dioptres (D).

This method has several advantages. First, the visual angle can be regarded as the product Dx, which is then obtained in units known as prism dioptres (Δ). Second, a swift comparison can be made with both the amount of accommodation needed to focus the object, and the power of the spectacles. Fig. 1 shows how two objects at different distances can subtend the same visual angle.

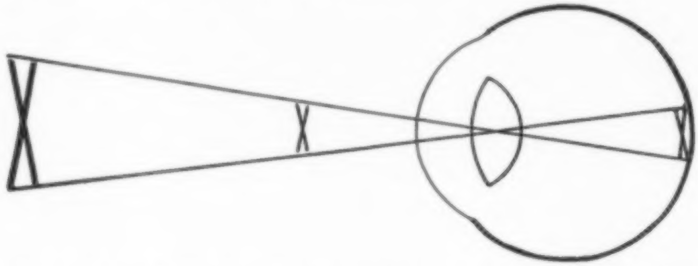

FIG. 1. The visual angle. The dimensions of the critical detail, such as the size of the letters X shown in the figure, must be taken with the distance from the eye before the visual angle can be determined.

The true dimensions of the critical detail are sometimes hard to establish, as indicated in Fig. 2. In most cases measurements can be made directly or photographically, once it is certain what it is the observer really has to use as the retinal image. In reading, for example, the plane of the paper can be so tilted as to reduce the effective size of the detail. Stop signs painted on roads are made to compensate for this distortion. Magnification is often a good method of increasing the virtual dimensions of the task; the use of some magnifiers restricts the observer to a short working distance, even though the image he looks at is a relatively distant one. Binocular vision is impossible with some devices which magnify well, but projection can sometimes overcome the disadvantages of viewing through lenses. Fig. 3 illustrates a typical use of magnification.

Working distances are often fixed by the circumstances of a task, and other factors have to be made to fit in. Careful observation will frequently reveal that workmen have to use a range of distances for their nearer observations; in the case of a presbyopic (old-sighted) worker who is corrected with near-vision spectacles, difficulties

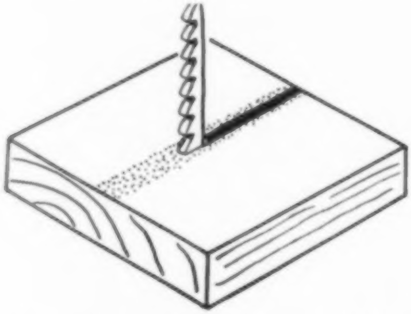

FIG. 2. Sawing along a pencil line. The actual size "x" of the detail is either the position of the sawcut relative to one edge of the line, or else the difference between the two undisturbed parts of the cut line.

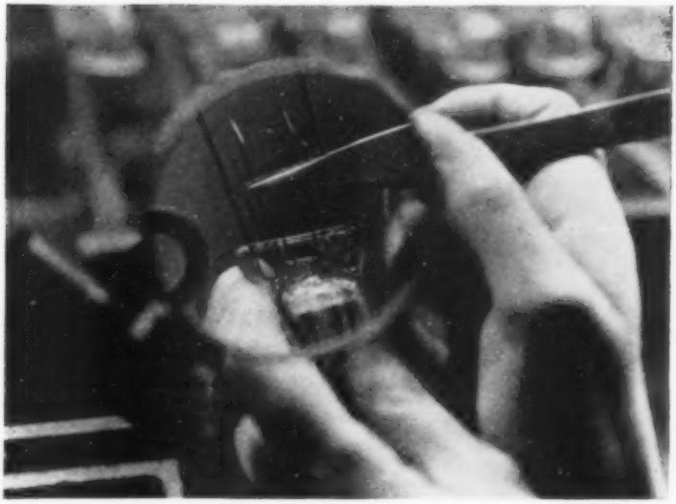

FIG. 3. Increasing the *Dx* factor by magnification (General Electric Company photograph). The apparent increase in the size of the critical detail may make it unnecessary to reduce the working distance.

FIG. 4. Forced increase of working distance (photograph by D. F. WAGSTAFF). An undercorrected presbyope tends to have to hold his work at arm's length to avoid the necessity for accommodation. This reduces the visual angle of the task.

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may arise because his prescription has too little depth of focus. In such cases special types of bifocal are sometimes indicated, or even the use (upon professional advice) of an old and weaker pair of reading glasses. It is typical for the uncorrected presbyope to lengthen his working distance, thereby reducing the visual angle and possibly making it even harder to see clearly (Fig. 4).

WESTON (1935) carried out an investigation of the performance of 18 subjects doing a "standard near task". Precautions were taken to rule out the effects of fatigue, practice, etc., and to reveal the relative merits of size and illumination. Illumination is well known as a means of improving performance, provided it is used correctly, and it is interesting to see in Fig. 5 how size can do the same.

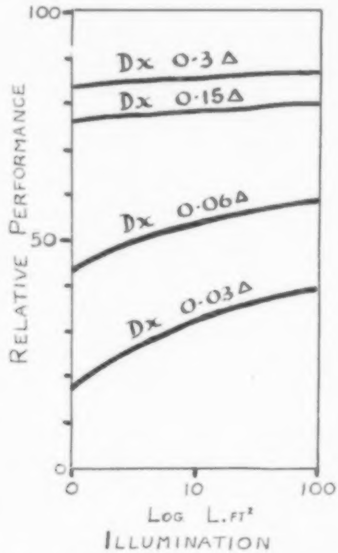

FIG. 5. The effect of size and of illumination upon performance (WESTON's data (1935) used). Size gave a greater benefit than a similar proportional increase in illumination for any given size of detail. Note that a Dx value of 0·03 prism dioptre is approximately equivalent to 1 min of arc.

Visual acuity is the matching capacity, taken with accommodation. Visual acuity as it is usually measured with a Snellen letter chart at 6 m can be a good guide to a person's visual capacity. It is only a distance test, however. Distance acuity can be reduced by such ocular errors as myopia and astigmatism, while at the same time the near vision acuity can be splendid. Separate estimations for distance and the near working distance are necessary. The latter can be carried out with Jaegar or "Near" charts, or on practical objects of known size. A person with 6/6 visual acuity can detect a gap or series of gaps in a letter 6 m away, the dimension of the gap being approximately 0·3 cm. The visual angle here is 1 min of arc, about 0·03 Δ. To have the same order of visual acuity at the "conventional" reading distance of 1/3 m, he must detect detail, the dimensions of which are 0·01 cm. Three dioptres of accommodation would be used for this near task, unless some of the "power" was provided by near vision spectacles. It must be remembered that myopes may have good near visual acuity and young hyperopes may have good distance acuity; in both cases it is

probable that spectacles would improve their general visual efficiency, a fact not revealed by merely testing acuity.

Ability to recognize letters or similar characters may not be a good "rating" for some purposes. If an engineer has to read a vernier or a slide rule it may be necessary to consider whether his "aligning power", a special form of visual acuity, is adequate. Fortunately vernier acuity is better than letter acuity in most people, but this may only be true for lack of alignment in vertical lines. In the same way "stereoscopic acuity", the ability to discriminate differences in the distances of objects, may be good for most objects but poor for lines or contours which are horizontal. Much can be done to improve the visibility of some tasks by utilizing these facts.

Good stereopsis is sometimes said to be essential for certain jobs. Crane operators and "spider men" may be taken as examples. It is true that some "natural selection" operates in industry, but many men without normal binocular vision have very good practical ability to judge distances. Many monocular clues such as overlay, size, perspective and shadow assist depth perception (Fig. 6).

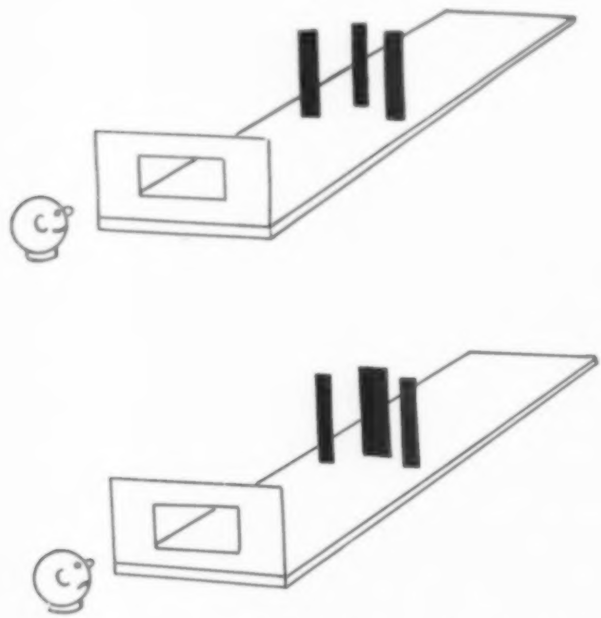

FIG. 6. Clues in depth perception. The subject is using the "three needle test". The retinal image sizes indicate that the centre object is farthest in the top picture, and nearest in the lower picture.

Binocular vision must frequently be taken into account when the mating of task and vision is considered. The convergence of the visual axes to a near task is yet another matter which must be taken with the "size" of an object, particularly if the object is very close. A condition of latent convergence, or divergence, of the visual axes from the correct position is often a cause of strain; with the onset of fatigue, double vision may supervene. This condition of heterophoria, or latent squint, can be induced by working conditions. In a number of young weavers working at an

FIG. 7. Engineer at the lathe, showing head position (B.E.A. photograph). Working posture such as this may induce right hyperphoria and attempts to correct this imbalance may spoil performance.

FIG. 8. Laundry finishing, the visual task including the detection of slight variations in contrast (photograph by courtesy of Crompton Parkinson Ltd.).

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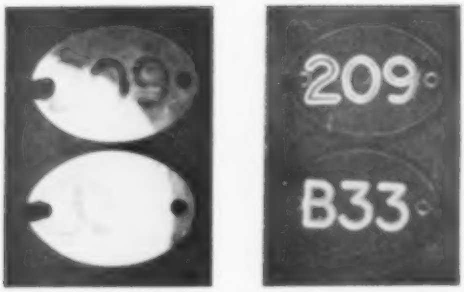

FIG. 9. Contrast variations according to type of illumination. Two number plates are shown, in which the characters are engraved into the back of perspex plates. 209 is not filled, B33 is filled with white paint. In the picture on the right side illumination reveals certain contrasts. In the left-hand picture specular reflexion (glare) has reduced the contrast and has also reversed it.

FIG. 10. An appropriate surrounding for a critical visual task (photograph by courtesy of Philips Electrical Co.). The readers, in a large publishing house, are provided with a good brightness ratio.

average distance of 15 cm, SUTCLIFFE (1950) found that esophoria was induced at the end of the shift. WESTON and ADAMS (1928) and others have proved the utility of providing special spectacles glazed with appropriate amounts of plus sphere combined with base in prism. The effect of such spectacles is to image the work at a position where a reasonable effort of accommodation can be harmonized with a normal amount of convergence. Vertical heterophoria may be induced by a habitual head-tilting during work. Lathe workers may exhibit right "hyperphoria" on this account (Fig. 7), in which cases steps to relieve the imbalance with vertical prism may be doomed to failure. Accident ratings of workers sometimes suggest the association of accident proneness with heterophoria. Performance and learning ability have also been shown to be influenced by heterophoria in some individuals but there are no infallible rules which apply.

2. *Contrast*

This component of the visual task is more straightforward. First, the contrast between the details of the task must be considered, then the contrast between the task and its surroundings. The term brightness ratio is sometimes applied to the latter. Contrast is obtained when two parts of the visual task, which have equal reflecting properties are illuminated unequally; for example, when a lantern slide is projected upon a white screen. The more frequent cause of contrast is the unequal reflexion of light from different components of the task; the printed page is an example. Specular reflexion is a common cause of glare which gives unwanted contrast but at times, as when scales engraved in a polished surface are viewed, reflexion may enhance contrast.

The Illuminating Engineering Society's recommendations use the terms "good", "medium" and "bad" contrast, since rough assessment is usually possible. More exact "rating" by photometric methods is difficult and, for practical purposes, comparison with surfaces of known reflectance, matching each component of the task in turn, should be used. In a host of occupations contrast can be readily improved. In some industries, such as the laundry and some textile industries, there is an effort to eliminate contrast; inspection may therefore have to detect minimal contrast and all the other factors conducive to visibility must be used to the full (Fig. 8). Glare must be regarded as a destroyer of contrast, since it tends to veil the retinal image with unwanted light (Fig. 9).

The brightness or contrast ratio between task and surroundings influences the visual task. It is considered good practice to keep the brightness (luminance) of the area immediately around the task just a little lower than that of the task itself (Fig. 10). The appropriate visual capacities depend upon the exact nature of the task but generally consist of visual acuity and brightness discrimination. Visual acuity, in fact, greatly depends upon such discrimination. For practical purposes visual acuity could be used as the visual rating, possibly with low contrast charts for occupations such as laundry finishers, textile inspectors and cotton graders. Serious loss of light sense, caused by retinal disease or gross vitamin A deficiency, is a contra-indication to work under low illumination, night driving or mining.

Colour contrast is of great importance in many occupations but the subject is too vast to be considered here. Suffice it to say that contrasts of hue and saturation may be employed to facilitate vision and the quality of the illumination must be chosen to avoid confusion. Paint and fabric matching is notoriously risky under the light of

filament lamps. The rating of subjects' colour vision can most satisfactorily be carried out, for this purpose, by plates such as the well-known Ishihara series. Colour vision defects must be expected in about 8 per cent of males; the most common form of colour confusion by defective subjects embraces all the changes in hue to which a tomato is subject, green, yellow, orange and red.

3. *Luminance*

All the factors assisting visibility are interdependent. It is therefore impossible strictly to separate luminance from the rest. High reflexion factors can be used as a means of obtaining luminance but illumination is the variable which is most often considered. The techniques of illuminating visual tasks are now well known and the benefits of adequate amounts of suitably applied illumination do not require restatement here. In the rating of a task with respect to luminance there should be an attempt to assess the reflexion and to see if it can be improved; matt surfaces may well be substituted for glossy surfaces in some cases. Next, the intensity of illumination should be considered in comparison with modern recommendations for the type of work. Moss (1947) suggested on the basis of data provided by WESTON (1935) that for visual tasks subtending about 1 min of arc the illumination in lm/ft^2 might be estimated as equal to $60/(\text{size in min})^3$ if contrast is good. Correction factors of 3·3 and 10 should be applied for "average" and "poor" conditions of contrast respectively. In the event of the luminance of a task being affected by glare conditions steps must obviously be taken to minimize the glare; industrial situations frequently demand the use of selective filters to reduce special types of glare, including polarizing methods where applicable. Attempts to evaluate the "capacity" of workpeople to stand

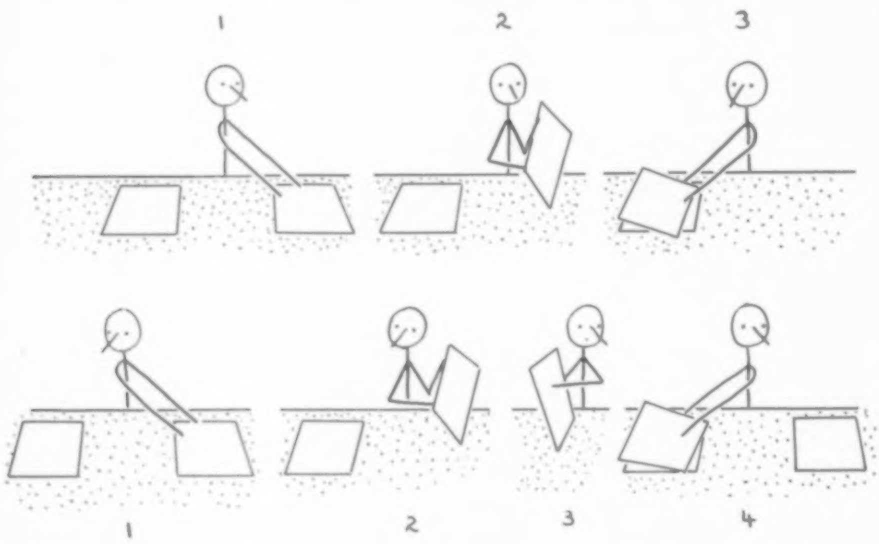

FIG. 11. Process revision allows more time for vision (after Tiffin and Rogers). A tinplate-sheet inspector is depicted. In the three top sketches his gaze follows his hands as he turns the sheets from his left to his right. The lower sketches show how, looking at the stationary surfaces, he can be given a greater time to detect flaws.

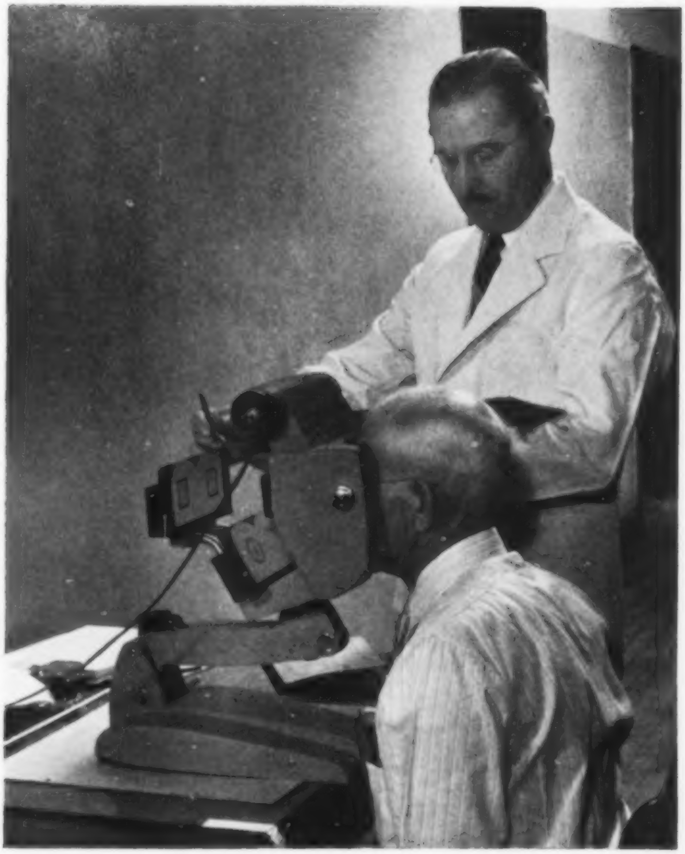

FIG. 12. A typical visual screening device (courtesy of Keystone View Co., U.S.A.). The device depicted is in direct line of descent from that first used by E. A. Betts for the screening of school children. Numbers of vision screeners have been developed, with differing merits.

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extremes of luminance are of very limited use. Photophobia may be an important consideration, as may night blindness. In aged people, especially, clouding of the ocular media, e.g. cataract, can be a source of aggravation of the adverse effects of too much light entering the eye. On the other hand, the small pupils, low media transmission, drooping lids and slow retinal response of the elderly may indicate much more luminance than for the young.

4. *Time*

Visual perception takes between about 0·01 sec and 0·30 sec, according to the circumstances. The attributes of both task and observer can affect this time. One important aspect of timing in industrial vision relates to flickering lights or to stroboscopic effects connected with moving parts of machines. The foveal perception time is roughly the same as the duration of the shortest fixational pause of the eyes during critical vision, but blinking and poor co-ordination of vision with movements in parts of the task can complicate the issue. Fixation is at a disadvantage if vertical, rather than horizontal, eye movements have to be made. It takes longer to focus the eye's optical system for near vision than it takes to relax accommodation; KIRCHHOFF (1940) found average times to be respectively 0·5 sec and 0·4 sec. Fatigue may increase "positive" accommodation but "negative" accommodation is virtually unaffected. The young can refocus more quickly than the old.

The rating of vision in terms of perception time may be applied to certain tasks where time is all important. Tachistoscopic observations should help in assessment of individuals; practice in such observations will frequently improve capacity for rapid vision. Much can be done by process revision (Fig. 11) to allow more time in which to see the critical details of certain tasks, and subjects can be taught not to blink at the wrong moment. Tasks can be inspected to see if extraneous factors such as dust, noise or hazards are over-conducive to blinking.

5. *Task format*

The physical and psychological factors concerned with visibility are not strictly separable. The design and layout of tasks may influence the way in which an individual responds; the whole range of perceptual abilities of the individual is affected and little can be done by way of mating. Personnel selection by such stock methods as "form boards" or written intelligence tests should be based upon differences between successful and unsuccessful workers. Dials and scales must be designed for minimum confusion and maximum visibility, for example, using scales of ten which are divided into units of one. Altimeters should have the zero at the lower end of the scale, rather than at the top.

HAZARDS

It is worth considering the problem of ocular hazards in the context of visual tasks and visual capacities, since so many tasks involve hazards. Visual capacity can be totally destroyed or weakened as the result of radiation or trauma. The correction of sight with lenses is bound up with both task and capacity; lenses may possibly add to the risks or reduce them. It is common for stout goggles and other individual eye protectors to be provided in industry, only to be ignored as cumbersome or awkward. In a majority of such cases workers will be substantially protected if they wear spectacles. The spectacles should be robust but elegant and the lenses may be toughened glass, laminated glass or plastic.

The effects of enhanced visual capacity, for instance when ametropia is corrected, are felt in the prevention of accidents of all types. Thus one factor in accident proneness may be overcome sufficiently to enable a person to be entrusted with a relatively dangerous occupation when his visual capacity is improved to "match" up to the task.

VISUAL SCREENING IN INDUSTRY

The ideal method of mating visual tasks and visual capacities would be to enable every worker to have a full ophthalmic examination and for every ophthalmic medical practitioner, or ophthalmic optical practitioner, to visit every patient's work. This is not possible and present trends in practice seek to enable those who most need attention to be screened out from among their fellows so that they can be referred. A modified examination by a qualified practitioner can often yield good results quickly. Great strides have been made in recent years in the use of special devices which can be used by factory nurses, or welfare officers, to screen the vision of employees. Many of the techniques applicable to "Mass X-ray" examinations can be used in introducing visual screening. It should be stressed that visual screening must be under the control of a suitable practitioner, who is responsible for the standards set for referring different types of individual. It may be useful to refer all those whose distance or near visual acuity is found to be less than, say, 6/12, but only in certain occupations will it be necessary to refer people who cannot pass the stereoscopic test.

Screening usually includes the investigation of the following, both for distance and, separately, for near vision: visual acuity, right and left, heterophoria, both vertical and horizontal, stereopsis. Colour vision and field of vision tests may be added in special cases. It is very valuable to be able to include a check (such as "fogging") on

FIG. 13. Template of task. Certain tasks can be grouped as having the same visual requirements, the latter then constituting a "profile" of the task. Minimum requirements usually form a boundary for an aperture cut out of a template card. The card is placed over the record of performance on a screening test to see if the individual can fit the job.

latent hypermetropia. Carefully-planned screening should take up about* 5 min per person. The record must be examined by or according to the dictates of a qualified practitioner. A report should be given to the employee to the effect that he is either shown to stand in need of a further examination of his eyes, or that he came up to the standard laid down. It is stressed that the device does not give a full eye examination. Management may require a report, although it is a moot point whether records of this nature are the property of management or of the medical officer. Every precaution must be taken to avoid suspicion on the part of employees that this is a "weeding out" measure. The accent must be on bringing people up to a satisfactory standard.

In the selection of new applicants for jobs, screening can be extremely useful. Hosiery manufacturers, for example, invest a lot of money and time in training workers. Visual aptitude for tasks can be tested most readily by screening methods and many cases can be cited where the resulting placement of workers has been very rewarding.

In one textile factory all 4000 workers were screened. In one department alone 113 were referred for fuller tests. Of these, 70 took the advice and consequently 27 out of the 70 increased their performance. Of the 43 who ignored the advice, only 1 person was found to increase performance. Much information has already been accumulated to prove the worth of screening in industry, but screening must be used as part of a bigger process of rating visual tasks and visual capacities and mating them wisely.

Acknowledgement—The illustrations have been taken from *Ophthalmics in Industry*, a new book now being published by the Hatton Press Ltd., to whom the writer is indebted for permission to use them.

* The author has designed a device, the Fleming Master Vision Screener, whereby all the necessary investigations can be carried out in under 3 min.

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DISCUSSION

Dr. A. D. K. PETERS (Ministry of Supply) said what a pleasure it was to have heard Mr. FLETCHER's paper, which showed no evidence whatsoever of lack of notice, thus proving that Mr. FLETCHER was a master of his subject. She was also very pleased to hear the author's tribute to Mr. WESTON, because although she was a comparatively latecomer to industry, ever since 1940 Mr. WESTON has featured in much of the instruction received by industry, and being a retiring man possibly it had not been appreciated how much was owed to him.

Referring to the question of middle distance, or what might be called "working distance" tests, they were all familiar with the distance test and the near test, but the working distance was not always the same as the bench distance. For instance, in textile factories there was a greater distance where people were scanning material quickly for defects. They stood farther back, at a distance which was more than was assumed to be mill or bench distance. Also when hoeing, if one had glasses for hoeing and weeding it made a tremendous difference. She wondered whether perhaps a mistake was being made and that it was the working distance which should be measured rather than the near distance. Although she had asked that question many times over a period of years she had never yet received a satisfactory reply.

There were the economic and social consequences of such a decision: who was going to pay for the glasses? If one set a standard of near vision and distant vision the worker would probably buy them for himself, but if one provided them for working distance the employer would be expected to pay. She believed that problem had been raised under the National Health Insurance Scheme. In the old days would people have been given a third pair of glasses?

On the subject of bifocal lenses, if somebody had a great difference between near and distant vision the ophthalmic surgeon would not give a bifocal with perfect vision for each because it was dangerous, so they gave them near vision which was not adequately corrected and distant vision which was not adequately corrected, so that when going downstairs they would not break their neck. So that a bifocal had neither good near nor distant vision and the person was therefore handicapped in doing his work even when he had had his near and distant vision tested. Those were practical snags which she had encountered during her experience.

With regard to the protection of spectacles, she recalled a munitions factory in 1940 where the girls handling explosives either had not got goggles or were not wearing them, and after an accident she had attended to one girl who fortunately had been wearing a pair of spectacles which had protected her eyes, but she had spent quite a long time removing from her lower lip endless fragments of glass which to her amazement had not caused any damage whatever. It was probably an odd freak case. During the blitz there was quite a lot of evidence in Liverpool that spectacles had protected people's eyes from injury, and the point of safety lenses had not arisen.

Mr. FLETCHER, in reply, pointed out that the prism dioptre was the unit to consider, and apologized to those who were not familiar with it. It incorporated not only the size but also the dioptral distance, so that usually it was possible for an intelligent prescriber—and the word "prescriber" was important in that context—to go in between the distance acuity and the near acuity, not to average them but at least to evaluate them in terms of a visual angle at a given dioptral nearness, and he believed that was the answer. There was no simple answer to the intermediate distance problem of the presbyope, but there were a great many partial answers which should be tried and so often were not tried. The trifocal was only one of many, and admittedly under some circumstances that had its own particular difficulties.

His own responsibility at the Northampton College was largely the training of ophthalmic opticians, and that was one of their kingpins; it was where theory and practice were put together. A prescriber must intelligently assess all the characteristics, both subjective and objective, and put them together.

In relation to spectacles and the dangers thereof, his own lenses were plastic but more and more in the immediate future there would be an emphasis on toughened lenses and on safety lenses in the form of laminated lenses. Many new plastics were being developed along those lines. He had never seen a case of even a glass contact lens which had been damaged and had damaged the eye, and in his opinion the spectacle was by far the best method of protection and the hazards it would prevent were very much more than the hazards it would produce, except perhaps in the case of a myope with a very very thin centre to the lens, where efforts had been made to make it look nice.

Concluding his reply, Mr. FLETCHER said he was not there to sell spectacles any more than other people were there to sell light, but he would suggest that occupational spectacles should be looked at in regard to occupational hygiene.

Dr. J. R. GLOVER (Westinghouse Brake & Signal Co.) said that in his firm there were all sorts of occupations and the really dangerous one with regard to eyesight was undoubtedly the use of the chip hammers in the fettling shop; there had been cases where men's own spectacles had been broken behind gauze safety spectacles, consisting of Triplex glass in the front and with gauze round the sides. The firm very willingly agreed to pay for those men to have toughened spectacles, and they paid the difference under the National Health Service.

On the question of spectacles being worn by people engaged in work on grindstones, he did not think that many men lost their sight. They certainly got particles in their eyes and those particles had to be removed, but he believed it was a bit of a myth to say that ordinary spectacles were not adequate protection for grindstones. He believed that unless a grindstone exploded, or something of that nature occurred, although it would be infinitely preferable if they were of plastic or toughened glass, nevertheless ordinary glasses were an adequate protection for people working grindstones. People who had any sort of hammering to do, such as breaking up castings in experimental work, and even chopping wood, were in a far greater hazard to their eyes from the point of view of lost eyesight than people working grindstones.

He would like to ask if there were cases actually known, (*a*) where a person had lost his eyesight through a hot particle from a grindstone, and (*b*) where eyesight was lost due to glasses breaking, either in an accident or in industry.

Mr. Fletcher, in reply, said his own limited experience in that particular field had not produced any such example as Dr. Glover suggested. He felt that if they were going to look at it from the mercenary point of view alone they must not only consider lost eyesight but also lost time, and the grindstone was probably the chief offender. Every little workshop had a grindstone and it was used intermittently by people who usually did not bother to put on a pair of spectacles or goggles. If there was a shield for the front of the grindstone that was fine, provided it had not been taken off by somebody. He believed that if such things were actually costed it would be found that they were costing an awful lot of money.

To illustrate the subject of visual screening as a method of rating vision, Mr. Fletcher demonstrated a typical model of a device not available in this country. The particular model was the American Optical Company's "Sight Screener" in which a single knob is used rapidly to present a series of seven visual tests, first for "distance" and then for a near working distance. The lecturer favours this type of device rather than others.

Dr. G. J. Fortuin (Philips, Eindhoven, Netherlands) asked whether the instrument was capable of measuring visual powers greater than normal. Mr. Fletcher had defined normal as 6/6: for the older age that was magnificent but for the younger people it was insufficient, and when young people were employed it would be a good thing to be able to measure the greater than normal visual performances.

Mr. Fletcher, in reply, said the instrument was loaded with one slide out of a series which could be loaded into it, and the intelligent use of the instrument would necessitate the use of an appropriately sized target according to the job that it was intended to do. Otherwise he entirely agreed.

Mrs. McGrath (London School of Hygiene) said that Mr. Fletcher had suggested in his lecture that more harm than improvement was done by the use of prismatic lenses. Would he say that was generally the case with the use of spectacles and that more could be done with visual training and exercises to improve the eyesight?

Mr. Fletcher replied that he had been disappointed in life. He was disappointed with orthoptics, as it was known, as a science as he had himself dabbled with it. Therefore the utility of his opinion could be evaluated in those terms, but he would say that prisms were not used as often as they should be, especially in a transition stage, even with a convergent squint.

Mr. Langdon (Building Research Station) asked whether Mr. Fletcher's remarks would also apply to a situation such as had been suggested, using a lower-power aniso-eikonic lens.

Mr. Fletcher, in reply, said when considering the aniso-eikonic lens—and he preferred that term because he believed it was grammatically and derivatively correct—they were talking about one which had specifically no back vertex power, and that could quite justifiably include a prism. In his opinion the purpose for which that lens was used was divorced from the purpose for which a prism was used. He was not suggesting that everything should be divorced from everything else, but usually the two criteria did not have to be considered in the same patient, and therefore there would appear to be no connexion at all.

Dr. P. J. R. Challen said he had found the lecture most stimulating and the point which had particularly interested him was the instrument which Mr. Fletcher had demonstrated and which he believed it was right to call the Orthorater.

Mr. Fletcher, in reply, said he had been careful to bring along an instrument which was not on sale in this country. The instrument mentioned by Dr. Challen was a completely different thing and in his opinion it was not so good—but that was merely his opinion!

Dr. Challen said he gathered the instrument shown by Mr. Fletcher was along the same lines, although superior. He had been in industry a long time and was used to seeing the doctor or the nursing sister test vision with a card: sometimes it was a very dirty card, the illumination on which was very poor; sometimes it was improved in that it was in a box with fairly uniform illumination, and then the near vision was tested and that was about all. He and his colleagues went round their industries pretty often and they reckoned they knew the jobs and the vision that was needed for them, but he had been feeling for a long time that a start should be made on thinking about the problem more seriously. Theirs was a preventive medical service and there was a field for prevention. If they

were going to examine people's vision they should do it thoroughly, including muscle balance, and if necessary pass them on to the optician or the family doctor. It was about time the subject was taken more seriously.

Mr. FLETCHER: Hear, hear!

Dr. J. R. GLOVER, referring to the question of supplying glasses for working distances, said many working distances appeared to him to be only just beyond reading distance. Was it possible to read by extending one's arms a little more than usual?

Mr. FLETCHER, in reply, said it was possible but it might not be suitable. There was always a point where the thing became sub-threshold, and that might be it.

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MODERN METHODS OF ARTIFICIAL LIGHTING

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INTRODUCTION

THE words comfort and discomfort have already been mentioned in papers read earlier at this conference, and it seems right that we should try to make sure exactly what we mean when we apply these terms to lighting. We all know that the presence of the one means rather more than the absence of the other. A comfortable chair, for instance, has a positive attraction, but it is important to remember that to be really comfortable it must suit exactly your particular mood or requirement of the moment. If the chair is too low or too high or too hard or too soft, we immediately become conscious of the chair rather than its comfort.

When we think of comfort in lighting we think also of something that is positive in its contribution to our comfort, and is suited to the needs of the moment and is neither too hard nor too soft. In the case of industrial lighting it would seem that fundamentally we are concerned to give the eyes and mind the opportunity to work without distraction, to make efficient seeing the criterion of goodness without anyone being conscious of the lighting system that makes this possible. It is well known that lighting by means of candles is "restful" and indeed the lighting is of such a nature that it is hardly possible for it to cause discomfort. No one could say, however, that the lighting is adequate for any industrial occupation which needs accurate vision, and it cannot, therefore, be "comfortable" for this purpose.

Present-day light sources with their high luminance and efficiency have made it easy to provide ample light but they can also very easily cause discomfort, and in fact the more light we provide the more difficult it is to ensure comfortable conditions. For example, the illustration (Fig. 1) shows a drawing-office lighted by a multiplicity of enclosed globes using 300 W lamps. The illumination value of over 30 lm/ft^2 is good but the discomfort caused by the fittings themselves is considerable. What is required is the "lighting" without the "lights". The installation was replanned with a partitioned ceiling forming an overall louvre system and using fluorescent tubes as the light source and this system is illustrated in Fig. 2.

In the first illustration an attempt had been made to reduce glare by enclosing the lamps in large diffusing globes and these have the effect of reducing the brightness of the glare source, but the result would have been satisfactory only at low levels of illumination or in a much smaller room. In the second illustration the glare has been reduced by providing a cut-off so that the light sources are not seen at normal angles of vision and the result is much more satisfactory.

The illustrations show two methods of reducing glare, and in fact only these two methods or combinations of the two are available to the lighting engineer in his attempts to separate "glare" from "light".

LIGHT SOURCES

If it is accepted that the levels of illumination now considered desirable for industrial lighting are much higher than they were only a few years ago, it is clear that this subject of comfort in lighting must become of increasing importance. In considering the methods by which greater comfort can be achieved it is necessary to consider the properties of the light sources which may be used. Table 1 gives a list of a number of modern light sources and it will be seen that the source luminance varies very considerably. Fluorescent tubes in their early form provided a large source of such low brightness that under some conditions they could be used without screening or diffuser covers. The increase in efficiency of modern tubes is such that the luminance would normally cause discomfort unless screened in some way.

Filament lamps have a small source of light of very high luminance, and while this means that the lamps must always be screened or shielded from the eyes there is the advantage that such screens or shields are more easily contrived. The small source allows accurate reflectors to be designed which will give precise control.

Discharge lamps of the mercury vapour type have an elongated light source and are also of high luminance. They may be used either horizontally or vertically, but the shape of the source provides problems for the designer of suitable reflectors. These lamps are of good efficiency but for some purposes the colour-rendering qualities are not adequate and for this reason a combination of these lamps with filament lamps is frequently used. Figs. 3 and 4 illustrate blended lighting of this type.

Sodium lamps, although of high efficiency, are seldom used for industrial lighting because the colour discrimination is unsatisfactory.

PRINCIPLES OF GLARE LIMITATION

It has been said that glare from the light source is limited either by methods of cut-off or by providing diffusing enclosures or by combinations of these two systems. Where there is considerable mounting height available, however, the effect of glare is reduced, and in high bay installations the reflectors are used more to direct light on to the working area than to provide a useful cut-off.

It will be interesting here to consider the design of the ordinary industrial vitreous enamelled reflector. These are made with a cut-off angle of 70° from the downward vertical so that the lamp filament cannot be seen except in the case of nearby fittings. The interior of the reflector is white vitreous enamel to ensure the maximum efficiency, and indeed the reflector has a light output efficiency of some 80 per cent. Reflectors of this type are widely used both for tungsten and discharge lamps for industrial lighting but they have one disadvantage, that although the cut-off angle is satisfactory there may, under certain conditions, be discomfort glare from the reflector skirts. Conditions which make this skirt glare apparent are extensive installations of comparatively low mounting height, and some thought has been given to the possibility of reducing the skirt glare by the use of carefully designed reflectors which have a specular reflecting surface instead of a white one, the reflectors being designed to illuminate only a limited floor area. The object in a design of this kind is that reflectors seen from a distance should have a dark or almost dark appearance. The distant reflectors cannot be expected to provide useful light and it is therefore logical that they should be inconspicuous against their background. Fig. 5 illustrates an extensive installation in which the skirt brightness of the distant reflectors is quite

FIG. 1. Enclosed globes with 300 W lamps giving 30 lm/ft².

FIG. 2. Partitioned ceiling with fluorescent lamps giving 50 lm/ft².

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Fig. 3. General view of a blended light installation.

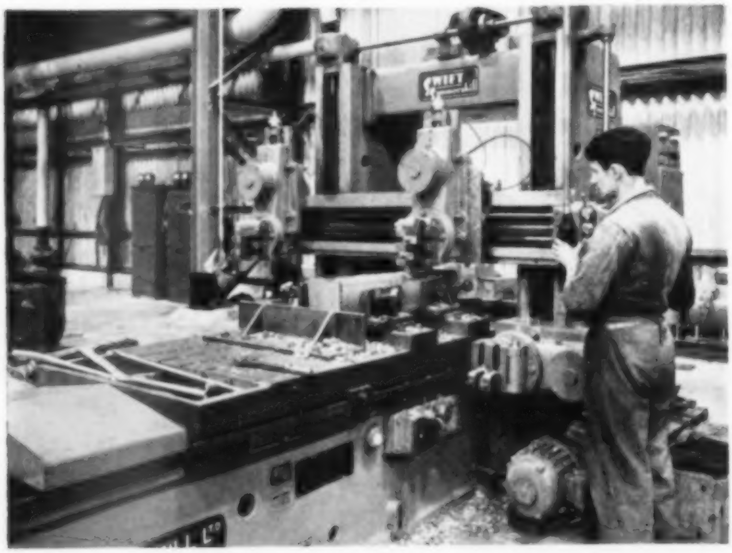

Fig. 4. Close-up of a machine under lighting as in Fig. 3.

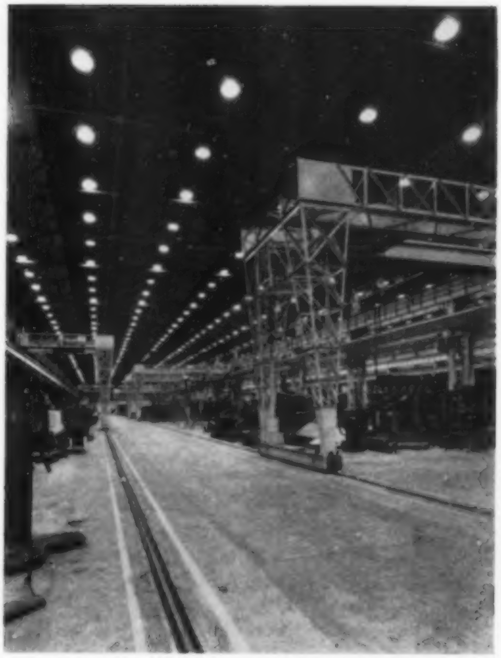

FIG. 5. In an extensive installation the skirt glare of distant fittings can be unduly noticeable.

FIG. 6. The central fittings give a greater downward intensity than the remainder.

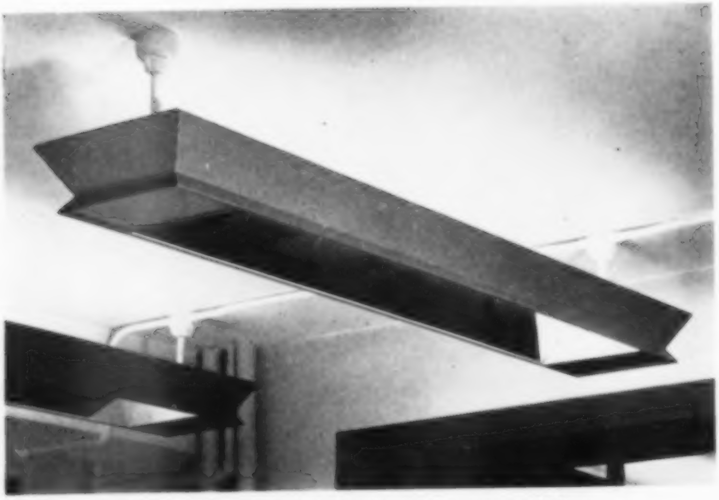

Fig. 7. Close-up of reflector type fluorescent fitting.

Fig. 8. General view of installation of Fig. 7.

noticeable. In Fig. 6 the central row of fittings has been changed to a type using a specular reflecting surface, and although these give a higher illumination at floor level the skirt brightness is much reduced. The differences are difficult to illustrate by means of photographs because the eye can appreciate a greater range of brightness than can be reproduced on paper, but the improvement in comfort by the use of this type of reflector can be quite marked, although the skirt luminance of the white reflectors is probably well within recommended limits.

Diffusing enclosures of glass or other material have also been used for glare limitation very widely indeed and we are all familiar with these enclosures of different shapes and sizes. The overall efficiency is less than with industrial reflectors because the walls and ceilings are directly illuminated, but the lighting is softer. This is the type of installation which may be quite satisfactory at one level of illumination but which may be very unsuitable at a higher level (see Fig. 1). The size of the room and number of fittings are other factors which will have a bearing on whether or not the result is to be comfortable. In a large area it is almost certain that the distant fittings, which contribute no useful light at the working point, will be a cause of some discomfort glare.

This type of fitting is usually suspended from the ceiling but the modern tendency is to raise them closer to the ceiling and provide openings in the bottom to increase the amount of useful downward light from nearby fittings. The brightness of the glass walls of the fittings is thereby reduced and the appearance of the installation improved, but the level of illumination must be limited if the appearance is to be entirely satisfactory. The more radical treatment of Fig. 2 allows almost any illumination to be provided without discomfort but the expense of such a conversion may be considerable.

A fitting for fluorescent tubes using specular reflecting surfaces has been developed which follows the principle described for tungsten and mercury lamps, and the reflectors of this fitting are quite dark when seen from a distance. It may indeed be quite difficult to tell whether all the fittings are switched on. A close-up view of this unit in operation is illustrated in Fig. 7. The design is chiefly useful for situations such as drawing-offices where all the occupants are seated looking in one direction because the cut-off is not effective along the length of the fitting (Fig. 8).

LOUVRES

If it is desired to control the luminance of a fluorescent lamp or lamps in a reflector seen end on, the logical step is to provide a louvre system. This may take the form of strips across the mouth of the reflector to provide an end cut-off comparable with the side cut-off or it may alternatively be in the form known as the egg-crate louvre. Normally such louvres are painted white but when this is done they reach a brightness which may be more than is desired, although they are considerably less bright than the lamps which they are shielding.

If the louvres are finished a dark colour or even painted black, the luminance can be reduced to any figure desired to obtain comfortable lighting, but there is the disadvantage that there is some loss of efficiency. The use of a specular material for the louvres is not a solution because the vertical faces of the louvres would reflect an image of the lamp at normal angles almost level with the horizontal [see Fig. 9(a)]. For specular louvres to be effective they must be set at an angle to the vertical, in which case they will appear dark when viewed from above a certain horizontal angle

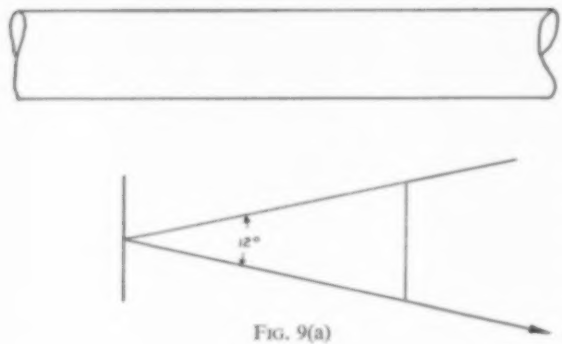

FIG. 9(a)

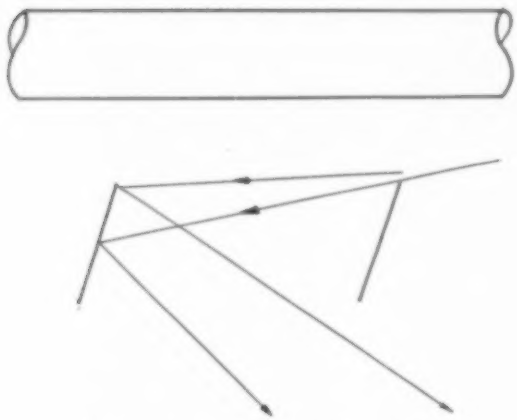

FIG. 9(b) Design of specular louvres.

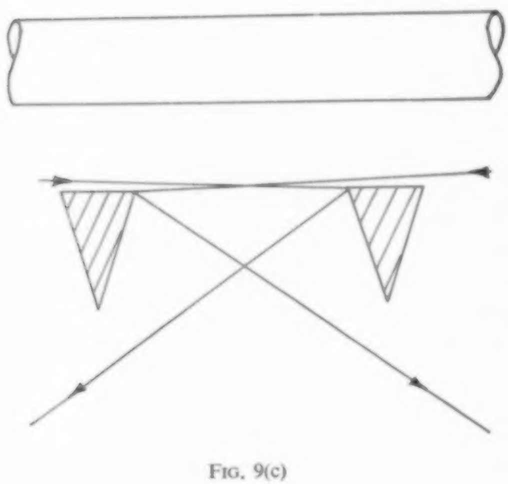

FIG. 9(c)

FIG. 10. Installation using fitting with stepped specular louvres.

FIG. 11. Non-corrodible "Perspex" fitting for 300 W filament lamp.

(Facing page 252)

FIG. 12. Non-corrodible "Perspex" fitting for one or two fluorescent tubes.

[see Fig. 9(b)]. A louvre of the type in Fig. 9(b) when used with a specular type trough reflector of correct design would ensure a dark appearance from normal angles of view from two sides and from one end. This arrangement may have useful applications.

If the louvre and reflector skirt are to look dark from all directions then the louvre needs to be of wedge shape [Fig. 9(c)]. This has the obvious disadvantage that the top of the wedge must obstruct a good deal of the light output of the lamp. To overcome this difficulty a type of louvre in extruded aluminium has been used which is in stepped form, allowing the working face to be set at the required angle while keeping down the thickness of the louvre.

An illustration of an installation using louvres of this type is shown in Fig. 10, and it is a remarkable fact that even a practised observer would estimate the illumination in the room at not more than 20–25 lm/ft^2, whereas in fact it is as much as 70 lm/ft^2. It should be noted that the brightness of the louvres is low enough to have been recorded by the camera.

This system of limiting the maximum fitting luminance at normal angles of view seems likely to be very useful with elongated sources such as 5 ft and 8 ft fluorescent tubes. The downward illumination is greater than that from a white reflector because the side reflectors more than compensate for the loss due to the louvres and an increased mounting height can therefore be used. The luminance from normal angles of view from any direction in plan can be reduced to a low value. This means that the more remote a fitting is from the observer the lower will be its luminance.

SOME SPECIAL PROBLEMS IN INDUSTRY

While, as a general rule, reflexions from highly-polished surfaces must be avoided as far as possible because they can cause discomfort and even disability glare, there are a number of instances in industry where these reflexions are used by the operatives in order to see what they need to see. An example is the trade known as "clicking" in the leather industry. The reflexion from the surface of the leather must be seen to follow the grain and to choose the position from which to cut the pattern. In another example from the printing trade, the "formes" of type must be checked. When the light source is reflected in the surface, the type can be clearly seen. If the angle is changed so that the reflexion is lost, the seeing task becomes much more difficult. In still another instance, in the motor-car industry the finish of paintwork is examined by using a reflexion of the source. In this case scratches and irregularities show up as imperfections of the image seen.

In these cases where the reflexion is intentionally seen by the worker it is necessary to limit the luminance of the source to a value which is sufficient for the purpose, and some experiment may be required to find what this value is.

FOOD FACTORIES

The provision of suitable lighting equipment for food factories is a subject which has received special study in recent years. The object has been to design lighting equipment which cannot, under any circumstances, cause contamination of the food being prepared. Obviously the fittings must have smooth exterior surfaces which are easy to clean and must be of a totally enclosed pattern, because electric lamps have been known to burst on failure and, if this were to occur over a food preparation bench, the whole batch must be condemned. The designer of the fittings must also

try to avoid using glass or metal because the former may be broken accidentally during the replacements of lamps and the latter must be painted or treated in some way for protection from moisture. If a painted metal fitting is found to have lost a chip of paint the assumption must be that this may have fallen into the food being prepared. Two designs which seem to solve these problems are illustrated, one for tungsten filament lamps and the other for one or two 80 W fluorescent tubes. The fittings are made entirely of "Perspex" without exterior metal surfaces (Figs. 11 and 12). These fittings being virtually non-corrodible are also widely used for chemical factories and laboratories where corrosion fumes are present.

LOCAL LIGHTING

It is true that many of the drawbacks of local lighting can be overcome if there is in addition a good system of general lighting, but it is also true to say that local lighting is frequently a cause of discomfort glare. While a local lighting reflector may be set at exactly the right angle and position to suit the needs of the operative who is using it, there is a strong probability that in this particular position it may cause irritation to other operatives in the vicinity. Local lights are now always provided with deep shades and these shades should not be tilted to one side unless absolutely necessary. Fixed local lights or local lights which are limited in the amount of sideways tilt are an advantage from this point of view.

The operative is always conscious of the presence of a local lamp and, though he seldom complains of this, it must be regarded as a drawback of the system. Ideal lighting will be engineered to give the vision required without any knowledge of where the light has come from. It is of course possible to project a narrow beam of light from a distance in order to give high illumination at a working point and this arrangement has many useful applications—spray booths, for instance, are often lit in this way with the added advantage that the use of flameproof equipment may not then be necessary.

While accepting that good general lighting is in principle superior to local lighting, this does not of course mean that local lighting should never be used. There are occasions when this type of lighting is essential.

Occupations such as watchmaking almost always require local lights to provide the very high illumination necessary as does also the close examination of small parts. Some such occupations do not become easier on the eye as the skill of the worker increases, and must be regarded for this reason as amongst the most difficult of industrial visual tasks.

The examination of the small steel ball used in ball-point pens may be quoted as one of these tasks. Each ball must be examined for imperfections or rust marks because these would interfere with the operation of the pen. One morning's work can usually be carried away in a watch glass.

Lighting for drawing-offices is an example where over the years there has been quite a controversy over the question of local lighting against general lighting. There have been occasions where good general lighting has been installed but the draughtsmen still ask to have local lights under their own control. Perhaps the reason is that the "good" general lighting has not been quite good enough. The problem is a very real one of avoiding shadows of T- and set-squares, and of avoiding reflexions from the paper and from the pencil marks on the paper. The position of the light source with

TABLE 1. EFFICIENCIES AND LUMINANCE OF LIGHT SOURCES

Type of source	Luminance		L/Watt
	cd/in^2	ft lamberts	Average through life
Tungsten			
200 W—clear	4000–5000	2,000,000	15
200 W—pearl	100	45,000	15
Fluorescent			
5 ft 80 W tube			
1942	3·3	1500	35
1958 (warm white)	5·5	2500	57
Mercury			
400 W—M.A.	1000	452,000	39
400 W—M.B.F.	130	59,000	44
1000 W—M.B.	5000	2,000,000	52
1000 W—M.B.F.	135	61,000	50
Sodium			
140 W	50	22,600	70

respect to the drawing table must be very carefully chosen if both these requirements are to be satisfied, and the angle of the drawing board is a related factor of great importance. An adjustable local light may solve these difficulties, but this does not alter the fact that such lighting can never be really comfortable to work with for long periods because the eye and mind do not have the opportunity to work without distraction. The best solutions of the drawing-office lighting problem have either a partitioned or louvred ceiling or use fluorescent fittings carefully positioned and designed to concentrate light from relatively high mounting positions. It is important that in a large installation the lighting units should be designed to be inconspicuous against their background.

In conclusion it is emphasized that, while modern and efficient light sources make possible high values of general illumination, the greatest care must be used in the design of fittings and in the planning of installations, if the overall result is to be of the highest quality.

DISCUSSION

Mr. CHRENKO asked the speaker if he would give a critical appraisement of the lighting in that lecture theatre.

Mr. PEIRCE, in reply, said for its purpose it would appear to be quite satisfactory and not too obtrusive. He did not like them to be quite so bright, although he did not think it really caused any difficulty in that case. As it was a lecture theatre presumably the lamps were not meant to be on all the time, although he felt quite sure it would not be satisfactory for working in.

Dr. F. P. A. GARTON (Hoffman Manufacturing Co., Ltd.) asked the lecturer if he could make any comments on the illumination of small gaps. He had in mind jobs where things had to be produced to profiles to very fine limits and the essential thing was to see whether one still had a gap between the profile and, say, the lathe tool. It was essential to have light coming through the gap.

Mr. PEIRCE inquired whether it was possible to do it by projection in some way.

Dr. GARTON said he was thinking of a production situation where the viewing had to be done every 5 or 10 sec as the tool was ground. There seemed to be a lot of conflict as to whether one should just have a black room and a bright light behind it, and he wondered what the reasonable compromise was between the intensity of the illumination one needed coming through a very fine gap of perhaps half a thousandth and the background illumination.

Mr. PEIRCE, in reply, said it should be as low as one could get it while still seeing well enough. It certainly should not be brighter than was necessary if one had to look straight at the light source.

Dr. GARTON added that a lot of the people present had probably listened to lectures in the new lecture theatre of the Engineering Department of Bristol University, and he felt sure that those who had would not agree that the lighting of the theatre they were now in was satisfactory.

Dr. HICKISH, reverting to the point about the recessed lighting fitting, said in his view the slides which Mr. PEIRCE had shown illustrated the point which he had previously made. It was surely fundamental to have a bright ceiling. Why, for instance, was the fitting not so designed that there was a gap of an inch or two?

Mr. PEIRCE, in reply, said that if the fitting was going to look dark anyway one could make it appear almost darker than the ceiling, but it depended on all sorts of things, such as the furnishing of the room. It was not at all necessary to say that in every case one must put light on to the ceiling directly. It was possible to get re-reflected light on to the ceiling and it need not necessarily look dark. If Dr. HICKISH saw the actual room shown in the slide, he did not think he would complain in any way of the ceiling variation. Anyway in these days people painted their ceilings black, blue and a good many other colours.

Dr. J. R. GLOVER said that a solution to that problem, worked out by his firm's plant engineer in a low-ceilinged room with fibreboard ceilings, consisted of two Terry clips with the light straight into them.

Mr. LANGDON said that, a ceiling being such a perfect redistribution surface, why not make use of it? His own feeling was that, in general, manufacturers did not pay sufficient attention to that. Very few of the fittings threw enough light upwards to make use of the redistribution properties of the ceiling.

Mr. PEIRCE, in reply, said it was perfectly true that the re-reflected light from a ceiling could be extremely valuable. On the other hand the neatness of recessed fittings was a thing that was pleasant to many people. They were often used with the "module" type of ceiling; such rooms were becoming more and more popular in large offices.

Mr. LANGDON said that if one was going to light the whole ceiling that was all right, but if one was not going to light the whole ceiling there would be patches of light and dark, and no matter what was done to cut down the brightness of the fittings, when Mr. PEIRCE spoke of it being a neat arrangement it was only neat on the architect's drawing and not once the light was switched on.

Mr. PEIRCE, in reply, said the lights need not actually cover the ceiling. In the case of a big office space where it was intended to divide it up into smaller offices, one wanted certain squares to be the lighting squares and one could have something hanging down from them or alternatively they could be louvred so that the light came more or less through. They could be put in alternate squares all over the room, which would certainly give quite a sufficient ratio of spacing/height to louvre the lighting fittings very closely indeed, and then the squares would not be any brighter than the ceiling itself.

Mr. LANGDON said he was not saying it could not be done. If in one way or another the brightness of the fittings could be equated with the brightness of the surrounding ceiling, he would agree that that kind of fitting could be used and it would look neat. At the same time one would be forced to go to considerable lengths and care in critical design to achieve what could have been simply achieved by using the ceiling to redistribute the light.

Mr. PEIRCE, in reply, said Mr. LANGDON was referring, almost, to indirect lighting. Whether the fittings were recessed into the ceiling or suspended from it, one still needed to screen the tubes in the two directions. One could put a bowl underneath and throw all the light on to the ceiling, but one lost efficiency, and totally indirect lighting was rather too soft for comfortable working in an office; one did want something in the way of a directional light, and the sort of directional light which came from a well-louvred fitting that did not look too bright from a distance appeared to be a very good

compromise as far as the appearance of the room was concerned. It also seemed to work very well, certainly in the particular installation about which he was speaking, as well as a plain recessed fitting.

Mr. Collins suggested that there might be another reason why Mr. Peirce's draughtsmen had insisted on retaining their local lamps, other than just elimination of shadows. The reason might also be partly psychological, in that they liked to have a bit of the environment under their control, and also possibly that they liked to be able to achieve a higher brightness on their drawing paper, or even perhaps on certain sections of their drawing paper, in order to assist them in maintaining their concentration on smaller areas in face of the distracting influence of other people's bits of drawing paper all round the office.

Mr. Peirce, in reply, said that Mr. Collins was probably right in his suggestion.

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COLOUR IN FACTORY BUILDINGS

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INTRODUCTION

IN this country we have been slow to appreciate and exploit the benefits offered by creative colour. From the earliest times when man buried his dead in red ochre, he has lived with colour and used it either for function or for beauty. But, until recent times, he has done this without fully appreciating many of the factors affecting his choice of colour.

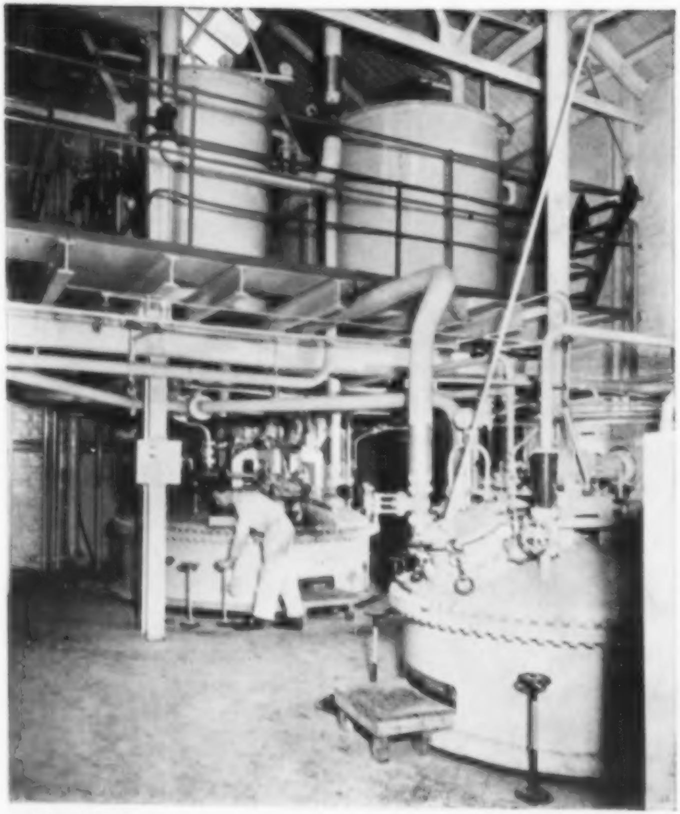
We in Britain have a legacy of distorted thinking from the Victorian and Edwardian eras when colourfulness was synonymous with commonness, and drab austerity and meaningless adornment of structure was the hallmark of quality.

It is true that until comparatively recent times we have been handicapped by a lack of technical knowledge regarding colour application; indeed, there was little stimulus to prompt research and development, but our modern colour chemist has provided us with an ever-increasing range of colours in paints, wall coverings, textiles and manufactured goods of all descriptions. Our problem now is not one of "What can we use?" but "Which shall we use?"

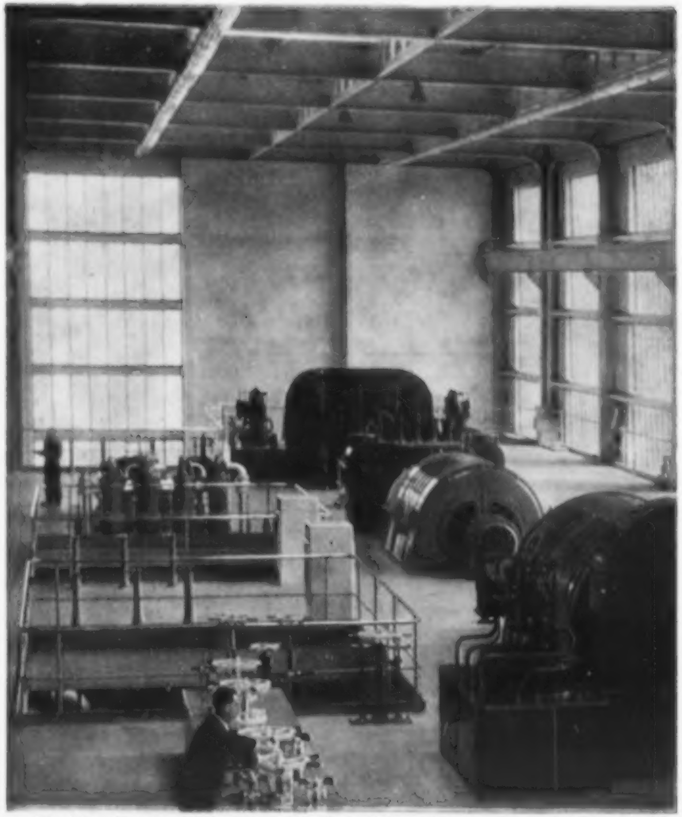
During the last 20 years or so much thought has been given to the problem of "Which shall we use?" in relation to colour in factories in particular and buildings in general. The real beginnings of controlled and publicized colour planning in industry can be traced, paradoxically, to 1940, when in the throes of war the value of colour as an aid to productive efficiency first gained general recognition.

The first publicity came from the U.S.A., accompanied by a typically American deluge of highly-coloured and exaggerated literature under such titles as "Three Dimensional Seeing", "Colour Dynamics" or "Sprayed Daylight" issued by paint manufacturers. From out of the resulting Brooklyn fog there finally emerged the fundamentally sound precepts of colour planning which formed the basis for early experiments in colour planning in Britain.

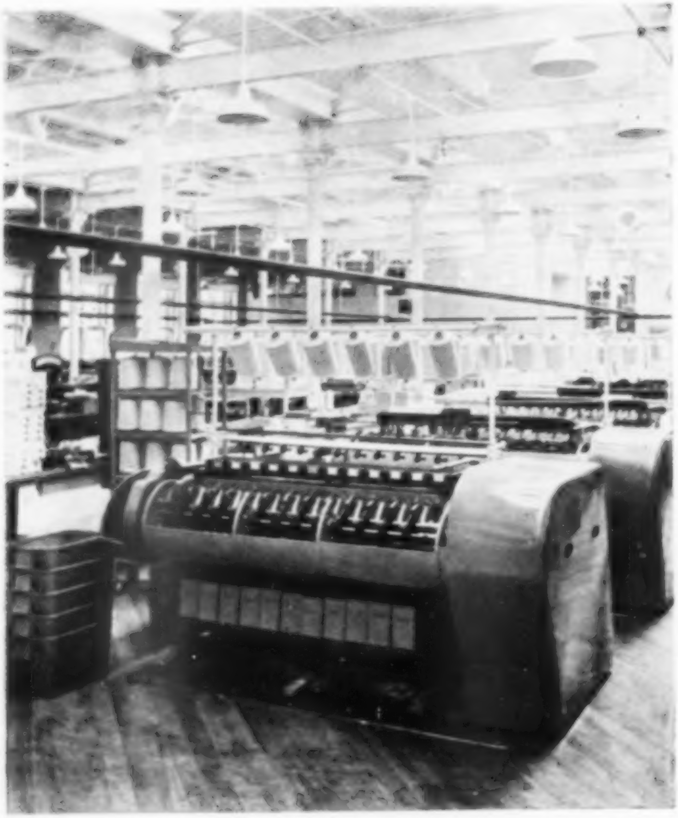
Early trials and experiments at home took place in 1944, initiated by the Cotton Board on behalf of the textile industry which was facing serious labour and recruitment problems, particularly the need to win older experienced operatives back to the mills, and to attract younger people into the industry. The first step was to induce mill owners to improve working conditions and introduce new amenities and services. Within two years in Lancashire alone a start was made in more than 600 mills in replacing the traditional whitewash and gloom with paint and colour. The Yorkshire and Scottish woollen industry was not far behind, and in Northern Ireland the linen mills began to experiment and introduce colour. And soon the more progressive companies in all fields of industry up and down the country were seeking information and experimenting within the limits imposed by the labour and material shortages prevalent at the time.



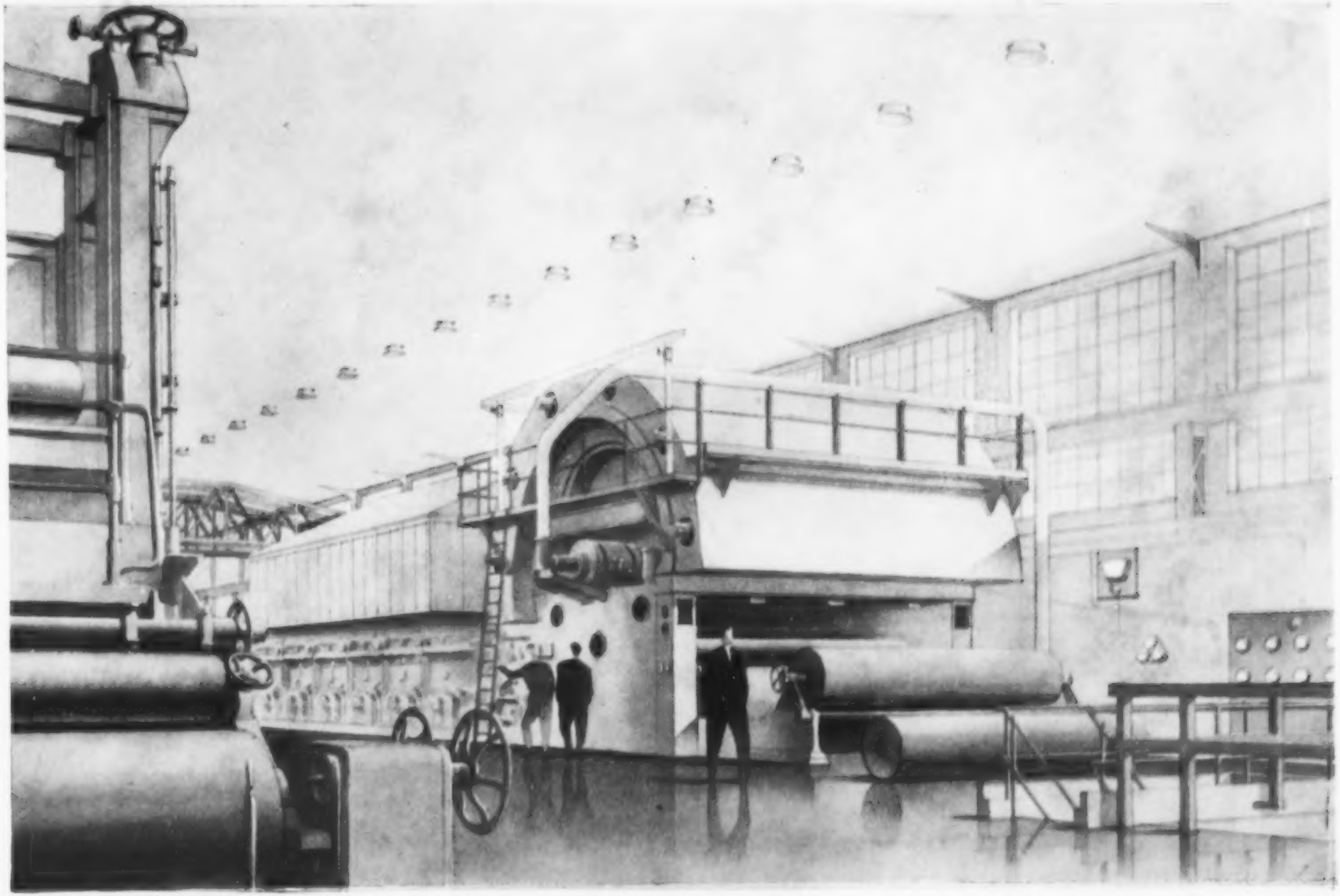
Grinding Room. (By kind permission of British Oil & Cake Mills Ltd., Trafford Park, Manchester.)



Turbine House, Main Power Station, Wilton Works, Imperial Chemical Industries Ltd.



Ball Winding Department. (By kind permission of J. & P. Coats Ltd., Mile End Mill, Anchor Mills, Paisley.)



Paper Making Machine House at West Mill. (By kind permission of Messrs. Albert E. Reed & Co. Limited, Aylesford Paper Mills, Larkfield, Nr. Maidstone, Kent.)

Today, interest in the use of colour in industry is widespread, not only in major industrial undertakings, but in the smallest of factories. Management and operatives alike are usually most enthusiastic, and having seen the results of colour planning are eager to do more.

COLOUR AND EFFICIENCY

Colour should, and can, provide a pleasant and comfortable working environment for employees. If this is achieved, other useful things follow automatically. The operative can work more efficiently because he can see better. Because he can see more clearly his job becomes less fatiguing, and if he is less tired his productive output can be sustained over a given working period. Better seeing conditions mean less time lost through accidents. These matters can play a big part in cementing good relations between management and employee. Good colour also means more efficient use of both natural and artificial lighting. In one American factory it was claimed that the available light was doubled merely by re-painting. This may sound incredible yet in extreme examples the improvement made is quite remarkable and could conceivably be of that order.

Thus colour in factories is not just a matter of aesthetic effect, but wisely used, colour makes a most important contribution psychologically and in respect of labour recruitment, welfare and works relations. Our purpose is not to impress the occasional visitor or just to satisfy the Factory Act, but to make a real contribution towards industrial efficiency.

These are bold claims. They are substantiated by prominent industrialists all over the country who have put the matter to the test.

COLOUR PLANNING

Much thought is very properly given to the planning and construction of new factory buildings today. The building is no longer a means of keeping the weather out and housing machines. Architects now consider the problems of layout in conjunction with heating, ventilating, lighting, dust extraction and insulation at a very early design stage, but, all too often, the question of colour is dealt with arbitrarily at the end of the job. The fact that colour can improve the efficiency of some of these essential services is either not understood or just ignored. Modern research has proved colour to be a specialist job and many architects are now finding it helpful to collaborate with colour designers at an early stage.

Light, colour and vision are interdependent. Just as the architect considers his building in relation to the scale and needs of the human occupant, just as the heating engineer considers his system in relation to bodily comfort, so the colour designer must consider colour in relation to seeing and the physical well-being of the beholder. It is not generally realized how strong a link there is between colour and comfort. Before colours can be put together in an effective and pleasing manner certain fundamental attributes of colour must be understood. The selection of colours is not just a matter of flair or taste. These must be supported by a knowledge of some very uncompromising properties of colour.

Extreme contrasts in brightness can contribute to physical fatigue. We have all experienced the tiring effect of walking round a large exhibition. This fatigue is largely due to eye strain caused by all the bright lights and bright colours competing for our attention.

BRIGHTNESS CONTRASTS

Our eyes are always attracted to the brightest area within their range of vision, and there is a time lag in visual readjustment between looking at an area of high brightness and then at an area of low brightness. The eyes adapt themselves differently when viewing light and dark colours together, and strain is caused.

In a factory this condition is often found where the walls are treated with white limewash or distemper and the machinery is black or dark coloured. To the operative this is both distracting and tiring.

An extreme example of such strain is produced when looking at the bright headlamps of a car approaching at night. The strong brightness contrast between the headlamps and the surrounding darkness causes discomfort. If we look at the same headlamps illuminated in daylight there is no discomfort because the brightness contrast is eliminated.

The effect of brightness contrasts in factories is less extreme but inescapable over long periods.

The cure lies mainly in painting machinery in light colours and so avoiding strong contrasts with background surfaces. The light machine colour also helps to reduce distracting highlight reflexions from rounded machinery surfaces within the operator's close range of vision.

Direct tungsten lighting on the job centre can also be a source of distraction. In the general lighting it is advisable to arrange for some light to be thrown upwards, and the painting of ceilings in white or very pale colours will reduce the contrast between lights and the area beyond.

Light colours used on plant and machinery give good light reflexion. This has obvious advantages in adding to the effectiveness of artificial lighting without increasing consumption of electricity, and also in helping the operative to see what is happening inside some types of machines such as hydraulic presses or large paper-making machines.

Dark-coloured floors absorb a great deal of light, soaking it up as a sponge absorbs water, except that the floor never reaches saturation point! Light-coloured floors serve a dual purpose in reflecting light and exposing dirt and untidiness, arch enemies of safety.

CHOICE OF COLOURS

In the actual choice of colours we are fortunate in that colour ranges are now much more comprehensive because of the increasing demand on the part of paint specifiers and users. But it is easy to be mistakenly led into choosing bright intense colours purely as a reaction to the drab and limited choice of the past. These are not necessarily the best with which to live and work. Bright stimulating colours have a tremendous initial impact, but can soon become tiresome.

Balanced colour schemes using substantial areas of neutrals are to be preferred for industrial use. By balanced colour schemes we mean treatments employing more than one family or group of colours. The eye quickly tires of absorbing only one colour because only one group of the cone receptors within the eye is being stimulated to transmit the colour sensation to the brain. The introduction of other colour groups spreads the work more equally around the colour reception cones and helps to reduce eye fatigue.

In choosing colour schemes all the coloured surfaces must be considered, existing floor or wall tile colours, the colour of any protective clothing worn by the operatives, and in particular the colour of the material being processed. A lathe, for instance, used for turning non-ferrous metal could be painted in a grey-blue, roughly complementary to the golden yellow metal being worked. The same colour might, however, be inappropriate on another machine processing a differently coloured material.

These are variable factors which can only be resolved in relation to a particular set of circumstances in a particular building. In relating these factors to the building the colourist must exercise his experience and judgment. Two important phenomena of colour should also be borne in mind.

In the solar spectrum some colours are light, e.g. yellow, and some deep, e.g. blue. Combined in that natural order in terms of depth of colour they will produce a pleasing effect. If the order is reversed (i.e. deep yellow with a pale blue) a discord results. This simple rule can be applied to all colours.

In the right surroundings such as in display or exhibition structures, colour discords can be used deliberately to stimulate interest just as in music a discord can be introduced to produce a dramatic effect.

When colours are grouped, each colour affects the appearance of others. A light colour seen beside a dark colour looks lighter, and the dark colour darker. Complementary colours in juxtaposition appear more vivid. Grey viewed with a strong colour appears to take on the complementary colour of the strong colour. Thus red will induce a blue-green tinge in grey. Colours should, therefore, be considered together rather than singly when formulating colour schemes. There is no such thing as an intrinsically bad or good colour. Colour can only be considered in relation to other colours.

These apparent changes in hue are the result of after-images formed within the eye. When looking at a strong colour, the eye becomes saturated with that colour and forms its image in the complementary colour. It is the overlaying of these after-images that causes the apparent changes in colours when viewed together.

Immediately two colours are put together the element of design is introduced. The shapes formed by areas treated must be considered and the proportions of these areas affect colour choice. Thus a vivid colour used effectively on a winding frame in a textile mill would probably be unsuitable for large paper-making plant occupying most of a room.

Desirable features can be accentuated and less desirable features made inconspicuous by painting out. An impression of height can be produced by vertical emphasis in colour treatment. Conversely, the appearance of reduced height can be obtained by horizontal emphasis.

Red, orange and yellow suggest warmth: blue, green and grey are "cooler" colours. These characteristics can be appropriately employed in relation to temperature or aspect. Warm colours give the impression of nearness, cool colours of distance, and can be used accordingly.

IDENTIFICATION AND SAFETY COLOUR CODES

Pipeline colour identification codes and safety colour codes are used in some factories. Discrimination should be exercised in the extent of application of such codes. Excessive use of identification or warning colours can mar the effect of a

thoughtfully planned colour treatment. Where these codes are adopted the colours should be considered in relation to the whole scheme, and restricted to bands round pipes or on elbows, junctions and intersections.

It is common practice to paint essential controls on machines, guards over moving belts, switch box covers and fuse boxes in bright colours. These items are usually in close visual range of any operator, and form an unnecessary distraction. The reason for this practice is hard to define, as there is no danger present when guards or switch-box covers are properly designed and in position, and the essential controls of a machine are not dangerous in themselves but as familiar to the experienced operator as the controls of a car to the regular driver. And who has seen a car brake painted red or orange?

The only time danger is present is when the guard or switch cover is removed, and for this reason it is more sensible to paint the danger colour on the *inside* faces of such items.

Generally speaking there is no reason to paint machine controls in any colour other than the main body except in the case of machines used for the instruction of trainees.

The foregoing indicates the wide range of varying factors to be considered. Each department must have individual attention, but should be dovetailed into comprehensive, balanced design. Implemented stage by stage, an effective, correlated colour environment can be created. Factories treated in this way are making no small contribution to happiness and productive efficiency at work, and to industrial welfare generally.

DISCUSSION

Dr. A. D. K. PETERS (Ministry of Supply) said that, having heard Prof. WRIGHT say that there was no physiological basis for harmony, she wished to look at the effect of light on the physiological processes of the body. Throughout the ages it had been well known that certain colours were associated with certain sensations, such as blue, which was a sedative, and red, which irritated people. That surely was related to some biochemical reaction in the body. It was said that the bull saw red and was irritated, and also work had been done on the growth of plants under different coloured filters. In medicine at one time it was taught that smallpox patients healed better under red light, but that had to be stopped because the nurses became so irritated. Then there was all the work in connexion with the relationship between light and egg production in the poultry industry.

There was obviously some sub-cortical centre which was related possibly with the endocrines and the production of adrenaline. What was the scientific basis which presumably went beyond the cones of the colour perception area? Surely it should be possible to get biochemical evidence?

Mr. JONES, in reply, said Dr. PETERS had raised a big subject. He was not a scientist and not competent to answer questions on the chemical processes involved; moreover, so far as he knew, no scientist specializing in the subject has given satisfactory answers to these questions. On the purely psychological aspect, of course, colour had associations, such as red for fire, and that in itself was quite an interesting study. Nobody had yet got to the bottom of the problem and had been able to say why, for instance, many reactions did take place.

For instance, he had done quite a bit of work recently on mental hospitals. He had talked to some of the doctors there and asked them if they could help in the preparation of the colour schemes, as to what colour would be a suitable one to use, and without exception they had said "We find yellow to be a very good colour", but not one of them had been able to say why. All they could say was "our patients seem to be more docile in surroundings of yellow than in any other colour".

Mr. LANGDON (Building Research Station) said he was not altogether happy about contrast effects in colour from the point of view of after-images. Although there were clearly some contrast effects which could be attributed to after-images there did seem to be phenomena which could not be

explained on that basis. For instance, if one took a piece of black cardboard with slots in it and poked a brilliant yellow pencil through and then moved it back and forth a distinct image of the rest of the pencil was seen whereas it was in fact behind the black cardboard. It disappeared, of course, as soon as one stopped moving the pencil.

That seemed to be similar to other types of change which could be produced in the image. For i nstance, one could produce changes in the apparent depth of a grey thrown on a white screen by allowing it to match with another grey which appeared to make it darker or lighter only so long as there was some relative movement.

It appeared that there was a phenomenon which was very closely related to simple after-image contrast effects but obviously could not be the result of them, and he thought it tended to suggest that even with so-called simple colour contrasts, to explain which the after-image explanation was usually invoked, there might be a more complicated process at work.

Mr. Jones, in reply, said that in his opinion it was quite possible that there were more complicated processes at work. Obviously what he had said in his lecture was a gross over-simplification of the problem. It had been introduced merely to show that such things happened and they had to be taken into account when formulating colour schemes. There was much work being done on the problem of the after-image but he had not yet seen a full explanation. He was not a scientist but an artist and all he could attempt to do was to show how artists took the facts which were presented to them by the research workers and interpreted them in devising colour schemes.

Dr. F. P. A. Garton (Hoffman Manufacturing Co., Ltd.) said he wondered whether they were not being a little too scientific. When all was said and done they were animals, and he wondered if the colours of blood, sky, grass and sunshine caused a psychological rather than a physiological effect. There was always a physiological effect following a psychological one which he thought might go far back into their ancestry.

Mr. Jones, in reply, said that being individuals they were all quite different: there were quite inexplicable basic reactions to colours in different people. It was something which was in the nature of the beast. Some people reacted very strongly to a pale blue, and he knew one man who actually felt rather ill if he was in pale blue surroundings. Why, he did not know. ("Comes from Oxford, I should think!")

He very often had people come up and ask him not to use green in a colour scheme because it made them feel unwell, and some people did quite honestly feel unwell if they were surrounded by a particular colour.

The Chairman asked how much of that was due to fashion.

Mr. Jones replied that he did not think it had anything to do with fashion, although of course fashion did play an enormous part in colour nowadays. At the moment it was fashionable to use nigger brown and lemon yellow together; next year it would probably be something else, but there again one should not confuse fashion with taste. That was another big subject in itself. Somebody might conceivably feel slightly uncomfortable if he felt out of fashion in a particular surrounding but he thought it would be a very rare case.

Dr. O. P. Llewellyn (British Celanese, Ltd.) asked whether Mr. Jones had seen the latest booklet of the B.S. Colour Recommendations.

Mr. Jones, in reply, said it would probably serve a very useful purpose in guiding people who had neither the time nor the inclinaiion to study in detail the use of colour. It was an excellent document and would serve a very useful purpose.

Dr. P. J. Chapman (National Coal Board) said, bearing in mind Mr. Jones' remarks about contrast and contrasting colours, had he any observations to make on the combination of the new high luminance paints with other paints of less brilliance?

Mr. Jones, in reply, said that, with regard to fluorescent and dayglow paints, only on one occasion had he used material of that type in conjunction with orthodox materials. He believed that when using those very bright, highly saturated colours one should display them against a neutral background. They are made very bright and intense for the sole purpose of attracting attention, so it is pointless to surround them with other bright colours. Used in conjunction with neutrals, as he had done on a display aircraft, they were quite effective.

The Chairman asked why those intense colours caused such annoyance to some people, although obviously not to all. He himself was irritated by them.

Mr. JONES, in reply, said they appeared to cause most annoyance really when they were shown off in conjunction with badly selected backgrounds. He had already made the point of complementary colours looking brighter in juxtaposition, and it was quite possible that the Chairman might be referring to such an example. Apart from that, when looking at those colours they did seem to vibrate, as it were, due to the fluorescent content of the material, and this was possibly causing some distress as well. They were hardly aesthetic materials in the true sense of the word.

The Chairman said he wondered if it was not more psychological than that. One looked with pleasure at a peacock's tail or a bird's wing which had those intensely brilliant, rather startling colours, but all shapes could bear a message to one and he resented a message being displayed in one of those colours which seemed to him to be unfitted to the dignity of that message. It was obviously a psychological point of his own, but he wondered whether it was general.

Mr. JONES replied that it might well be general because advertising functioned on that one particular point of thrusting the message home, regardless of whether or not one wished to accept it. It was probably good advertising but rather unpleasant to the beholder, although it certainly worked functionally in bringing such advertisements to one's attention.

The Chairman said that, if he might be permitted to argue with the lecturer, that again was a point which might be personal but he felt that an advertising message which was resented by the recipient might not always be useful. If he saw a message "Prepare for the Day of Advent" on a van which brought a message of a very different and rather unusual nature into an industrial city, if that were in a quiet grey he might be prepared to accept it, but if it were in a fluorescent paint he would resent it. Again, it was purely psychological, but very real.

Miss A. M. MITCHELL (British Colour Council) pointed out that they were rather talking as if fluorescent paints were available in the type of finish that would be used in interior decoration, and suggested that they had got a little bit away from the point because as far as she knew there were no fluorescent paints of the type which might be regarded as a decorative material. In fact she sincerely hoped not; the only place for that sort of thing was on posters.

Mr. JONES, in reply, confirmed that they were not yet available in decorative paints. There were durable materials available, but they were restricted to small features on, for example, painting certain aircraft, where one might want a bright line. Generally they were confined to poster, advertising and display work.

Dr. G. THOMAS said he was rather interested in the fluorescent paints because under certain circumstances where colour coding was important it might be imperative that an operator was able to see a particular colour under difficult circumstances. For instance, he might be working in breathing apparatus, and the fluorescent colours would be of greater value under those circumstances.

Mr. JONES, in reply, said he imagined that in very extreme circumstances such as that they could be of value and they might be sufficiently durable. He believed the practice was to put on the material and then varnish the top of it in order to give durability. His own company did not make these materials although he knew they were available. They would always have to be used with discretion, of course.

Mr. LANGDON suggested that if they were to be used for safety purposes one would have to be very careful because the reason for their fluorescent quality was their exposure to radiation, and one would have to be sure that they were in an environment which had got some daylight. With a fluorescent paint of that sort one relied on it doing its job because of the fact that it was usually exposed to daylight, which contained some ultra-violet radiation. If one brought it into an artificial light environment which did not contain any ultra-violet it would not be any more brilliant than any other colour. Hence if it was to be used as a safety factor to attract attention one would have to be sure that all the circumstances under which it would be used would be ones where ultra-violet would be in the light.

Mr. JONES, in reply, said he had had something in his office for some 12 months or so which had been painted in one of those materials and it was satisfactory because it got light from the window all day. He had not tried shutting it away in a cupboard and seeing what happened after six months.

Mr. LANGDON suggested that all he would have to do would be to pull the blind and switch the light on, and if it was a tungsten lamp there would not be any fluorescence from the paint at all. If one took one of the super-washers such as "Oxydol", which contained a fluorescent substance to

make one's shirt brilliantly white, that would only work under daylight or a light with ultra-violet in it, so if it was put in a room with tungsten, or better still gas, the shirt would not look any whiter than any other.

Mr. JONES, in reply, said there would be no cause to worry unduly because he had seen some of the fluorescent materials which had lost their fluorescence and the actual intensity of the colour was still very strong. It was still a very saturated colour.

Dr. J. M. McLINTOCK queried the statement about fluorescent materials not showing up in artificial light unless it had ultra-violet in it. He seemed to recollect a large number of cars with the bumpers festooned with tape with a fluorescent paint on it which fluoresced very nicely.

Mr. LANGDON remarked that it was not fluorescent; it was a reflector effect.

Dr. O. McGIRR (B.O.A.C.) asked the lecturer if he would comment on the treatment of large offices in regard to colour schemes. He had in mind the contrast between America and the United Kingdom; the tendency in this country traditionally was to have relatively small offices, but owing to American pressures and influences one was now seeing increasingly the use of very large osffices His own experience was in connexion with certain work carried out at Banstead Mental Hopital. and elsewhere in relation to the size of working groups and what was psychologically the suitable number of one's fellow human beings with whom one could work in a team, and it was believed to be in the region of 6, 7 or 8 people. Was Mr. JONES aware of any attempt to break up some of the very large offices into such smaller working groups by the use of colour?

Mr. JONES, in reply, said he had dealt with one very large accounting office which contained somwhere round about 1400 people doing all sorts of jobs in sections within the office. In that particular case the ceiling was broken up into squares and the floor was covered with tiles. Colour had been used to break up the floor space into areas of work, and panels had been painted on the ceiling in different colours over the particular sections, and it had been found that when standing at one end of the office it was possible to look down and say, "You see the blue ceiling—that is such-and-such a section". The walls were done in a neutral colour and the only brighter element of colour was the far end wall of that enormously long room, which had been painted in a strong colour in order to give the illusion of the room being slightly shorter than it was.

Dr. McGIRR referred to the Chase Manhattan Bank in New York, where there were perhaps 300 or 400 girls. It was very different from our principles of banking. One went in and told the most intimate details about an overdraft across a table, sitting next to somebody else at a similar table. Great attention had to be paid to furnishings and sound absorption, and the thing that impressed him was the gradation of colour; a dark skirting board going up to paler colours, to take away the feeling one got in an enormous office that the ceiling was oppressive, and the lighting, through plastic diffusers, relieved the monotony of it. He believed that was a tendency that would be observed a great deal more in this country.

Mr. W. BURT (Atlas Lighting Ltd.) asked whether, in planning a colour scheme, consideration was given to the light source under which the scheme would be seen, and whether any allowance was made for a change in that light source.

Mr. JONES, in reply, said that was a point which he had not made and it was most important because each different light source has a different spectrum, and colours appeared to change when viewed under these different sources. Those who visited the I.C.I. Paints Division at Slough would see in the Colour Advisory Studio a dozen or so lighting cabinets each fitted with a different type of light. When preparing colour schemes the type of lighting is one of the first things to be considered, and the limitations of some artificial light sources in colour rendering does present serious problems.

He had undertaken a job the previous year in Tynemouth, at a very large engineering factory where the employees were working all day and all night, three shifts every 24 hr. The general lighting at night was mercury vapour, which did dreadful things to colours because it was so short at the red end of the spectrum. He had had to devise a colour scheme which looked pretty well in daylight and also looked reasonable under night working conditions, and it had been a most difficult task. It is a matter to which much attention has to be paid by colour designers.

Dr. J. R. GLOVER (Westinghouse Brake & Signal Co., Ltd.) said water-colour artists in general had a horror of black, possibly because it was the opposite of the absence of colour. Could Mr. JONES say something about the use of black in industry, apart from contemporary schemes?

Secondly, the lecturer had said he liked to be called in at the design stage and it would be interesting to know whether the effect of various woods influenced him, and whether he would like to have some say in the choice of woods to fit in with a colour scheme.

Mr. Jones, in reply, said he could not recall a job where he had used black in industry. The water-colour painter probably did not use black because it increased the opacity of his colours, which of course he did not want. There would appear to be no reason why black should not be used in a factory, perhaps on a skirting where there was a lot of kicking.

With regard to the choice of materials at an early design stage, he regarded it as of the utmost importance. One had to take into consideration all the colours in the job, and of course hard woods, soft woods and, indeed, any other type of material—all had colour and all had to be considered in relation to the general overall colour scheme. The colour consultant could be so helpful in sorting out at an early stage the different types of materials to be used in conjunction with the paint colour schemes.

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LIGHTING THE OUTDOOR FACTORY

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INTRODUCTION

MANKIND is used to working in the open air, but the industrial revolution produced occupational conditions in factories which were the antithesis of the ideas of light and air. During the past 30 years, there has been a marked development in industrial production without the protection of walls or roof. The fuel industries including pit-head plant, gas works and oil refineries are increasingly making use of weather-resistant equipment, and the chemical industry is finding that some of its new processes operate better in free air than under cover, and that the cost of the building to enclose a large plant may be several times greater than that of the cost of the plant itself. Many of the heavy engineering industries are in the open air such as shipbuilding, and of course the civil engineering industries, including buildings, roads and bridges, are essentially an outdoor occupation. During the same period there has been a change in the method of lighting these outdoor factories. The original method was to use portable hand lamps with an occasional permanent lamp, giving a result akin to bad street lighting. The more modern lighting employs a number of techniques and designs of lighting fitting which will be considered in this article with special reference to the oil and chemical industries.

THE LIGHTING PROBLEM

In day-time, outdoor lighting is often thought by the layman to be perfect; actually, day-time lighting is not always good because the modelling of the object of regard and the shadows cast by it vary from very dull to very hard, and because the brightness levels vary from brilliantly clear to murky fog. Although these adverse conditions may be criticized on academic grounds, the operator usually manages very well in daylight for the simple reason that for most of the time he has plenty of light and can put up with its imperfections.

At night, however, there is great difficulty in lighting outdoor industrial plant. There is no diffuse reflexion from roof or walls to soften the shadows and to help the modelling of objects and the revealing power. There is no roof structure on which to mount an orderly array of lighting fittings, and there is no working plane on which to distribute the light according to the simple predetermined laws which are familiar in interior factory lighting. On the other hand visual requirements for outdoor industry are often much less exacting than those for indoor work; there is much less fine detail, and the outdoor tasks at night do not usually call for a high visual acuity. Many of the tasks are of the nature of routine checking, and there is a strong trend towards the grouping of meters, test points and so on in a central spot which permits the operation of the exterior plant from a warm, dry and brightly-lit interior control room. It follows that the exterior lighting may in some instances be required primarily for safety in access and for maintenance rather than for the actual operation of the

plant. The time may come when sufficiently high levels of illumination will be provided to permit fine work to be done and to allow for sudden emergencies, but at present these requirements are usually met by the old-fashioned method of taking a portable light source to the work.

The hazards associated with lighting equipment in outdoor factories are much greater than indoors. The weather is one of the most obvious hazards and is also one of the most potent. Reinforcing the attack of the weather there are a host of chemical corrosive agents associated with the factory production. Outdoor factories are often sited close to rivers or harbours and may have steam trains on their railways, all of which increase the rate of corrosion.

There is also the difficulty of erection and access. There is no single working plane and no principal direction of view, so it is often difficult to find a convenient position for a source of light. Having found this position it may be more difficult to put it there and often still more difficult to reach it afterwards for cleaning and maintenance. Cleaning may not be as necessary for outdoor fittings as indoors because the construction of the fitting may make it less subject to depreciation because of dirt. On the other hand, maintenance may be more important because the lighting fittings themselves may constitute a hazard, as for example in an area subject to the presence of flammable gases (the word "flammable" is replacing the better-known word "inflammable" in this connexion because it is less liable to misinterpretation by those unfamiliar with the English language). Flame-proof, explosion-proof and dust-proof fittings may be required according to the nature of the work, and these bring with them problems of construction and heat dissipation.

THE REQUIREMENTS

The amount of light which is provided in any particular area varies very widely according to circumstances; it depends both on what is needed and what it is possible to give. The desirable level of the illumination for particular visual tasks can generally be taken from the appropriate table in the "Code for the Lighting of Building Interiors" issued by the Illuminating Engineering Society. This level is usually much higher than is economically possible for the whole outdoor site and local lights are usually provided for the areas in which particular visual tasks have to be done. The other lighting requirement for safe movement about the factory is met by an adaptation of street lighting technique in which the lamps act as guiding lights and reveal obstructions by specular reflexion and silhouette vision. This type of lighting may of course be applied in very much smaller areas than the average street, and the illumination levels may be appreciably higher.

THE DESIGN OF THE INSTALLATION

This scheme of lighting leads to what is commonly known as a Christmas-tree effect as shown in Fig. 2, due to the large number of small light sources clustered around areas of particular interest. Individual plant units often have several hundred lights, half of which may be installed to illuminate the stairways and ladders to the numerous platform levels. The remainder provide local lighting for gauges, valves, general inspection, etc. Maintenance work is, therefore, laborious and it may be wondered why floodlighting is not employed, particularly in view of the advances in technique with this type of lighting, giving relatively shadow-free illumination of

FIG. 1a. Kwinana Oil Refinery. The maze of walkways, ladders, valves and meters presents special problems in lighting.

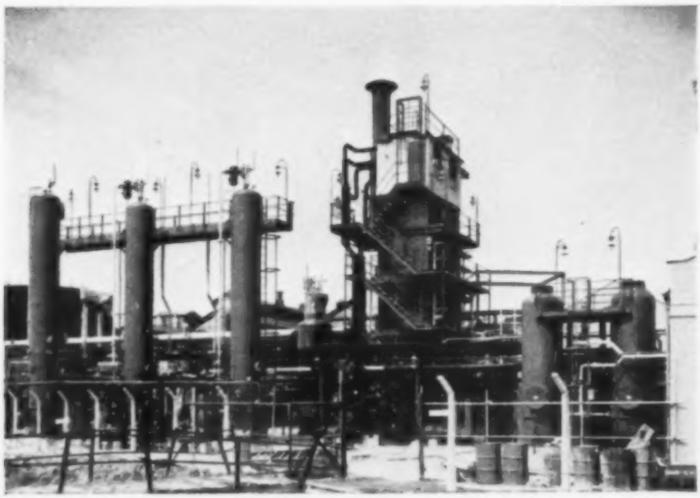

FIG. 1b. Hydrogen Plant. The different levels and the absence of background make local lights necessary.

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FIG. 2. Kent Oil Refinery. Flameproof lighting in an oil refinery.

FIG. 3. Grangemouth Oil Refinery. Street lighting, floodlighting and local lighting techniques may all be used in an outdoor factory.

FIG. 4. Billingham Nitric Acid Plant. Corrosion-resistant fittings installed to light the walk-ways.

FIG. 5. Corrosion-resistant 'Reflector-Bowl' lighting fitting. Detail of the lighting fitting shown in Fig. 4.

football fields or sports grounds. There are some installations where floodlights are employed to provide general illumination for movement, but obstructions in the form of cylinders, steelwork, etc., still necessitate the use of local lighting for gauges and stairways. Fig. 1b illustrates the hydrogen plant of Messrs. Laporte Chemicals at Warrington, which is an example of this type of dual installation. The initial cost may be higher, but it has the advantage of removing some of the light sources from the centre of the hazardous area to safer and more accessible positions. In many chemical factories and oil refineries, the plant units are so close to each other that floodlighting can only be carried out from two sides and the shadows would not permit any material reduction in the number of lights on the actual plant. Floodlighting is now accepted as one of the best ways of lighting railway yards, and it is employed in some instances for oil storage tanks of which Fig. 3 is an illustration.

It is very important to reduce glare, partly in order to reduce visual discomfort but principally in order to depress the level of dark adaptation and to reduce disability glare. It is also important to place the lamps correctly to avoid unwanted or misleading shadows, and to give proper modelling of the illuminated objects so that they are immediately recognizable and so that the effective level of visual acuity is as high as is permitted by the illumination level and the contrasts contained in the visual task. These two requirements are generally more important than the actual amount of light or the actual illumination levels in the visual field, and they represent the principal difference between interior and exterior lighting. In an interior, apart from having much more light, the lamps are generally mounted high enough to be screened from direct view, and the walls and other surfaces reflect diffused light which gives to the object of regard an appearance similar to its more familiar appearance in daylight. In an outdoor factory, cut-off reflectors, louvres, etc., may not be practicable, and considerable care must be taken, therefore, to reduce the peak luminance of any lighting fitting and to make its flashed area as large as possible so as to compensate for the loss of diffuse reflexion.

Figs. 1a, 2 and 3 illustrate the visual tasks and the lighting effects in an oil refinery. Most of the light is obtained from relatively small lamps in enclosed fittings, but Fig. 3 shows the two other principal methods of lighting, namely the ordinary street lighting technique for access lights and open areas and direct floodlighting, on the lines mentioned above, to give illumination at the tops of the tanks for safe movement and for reading the scales when checking liquid levels. Most of the lighting is done by filament lamps, because of their simplicity and small size in comparison with tubular fluorescent lamps. Sodium and mercury discharge lamps may be used in ordinary street lighting lanterns if the electrical complications of the auxiliary gear do not present any difficulties or any undue risk of corrosion or explosion. Tubular fluorescent lamps are generally restricted to control rooms, pump houses, etc., where their size does not present any problem of maintenance.

THE DESIGN OF THE LIGHTING FITTING

Figs. 4 and 5 show the lighting installation over walk-ways in a chemical plant where there was liable to be high humidity and transient concentrations of nitrous fumes. These fittings may be taken as an example of the precautions necessary to reduce corrosion. A glass bowl is used because glass is almost immune to normal chemical attack, and this is carried in a silicon-aluminium alloy casting fixed by

stainless steel screws. The castings are first treated by a chromating process before being sprayed with a red oxide priming coat which is then stoved, and an alkyd resin paint is then used for the top coat and is also stoved. The design of the castings and of the glass give a smooth outline with no crevices or ridges where dirt can lodge, and a lip is provided to shed water or corrosive liquids away from the gasketed joint. The fixing screws are on an under surface where they are protected from the worst corrosion. Such a fitting controls the light from the lamp by refraction and diffusion rather than reflexion, and it is general experience that a glass refractor will maintain its efficiency better than any form of reflecting surface. In this particular fitting there is an interior translucent glass reflector which serves to direct the light downwards, and also serves to reduce the luminance to a low value of angles of view near the horizontal.

ERECTION AND MAINTENANCE

The care taken in the design of lighting fittings must be balanced by an equal care in their erection, and in the electrical supply. If steel conduit is used it must be heavy gauge and must be spaced away from the surface on which it is mounted to avoid the collection of dirt and the resulting corrosion. Proper choice of protective paint will do a lot towards extending the life of such conduit. There is a growing use of plastics conduit and of mineral insulated cable in which the insulation is covered by a thin metal sheath which may then be covered by a protective sheath of plastics material such as p.v.c. (polyvinyl-chloride) or by wrapping with a suitable non-absorbent tape. Glands, switches and other electrical equipment must be made weather-resistant and corrosion-resistant, and again the protection of the surface by paint or by wrapping is helpful.

As already indicated, the careful design and installation of outdoor lighting must be supported by good maintenance. The working conditions in an outdoor factory are frequently such that the failure of a single light or of a small group of lights may create a dangerous situation. The maintenance costs of an outdoor intallation will always be greater than those of an installation of equal merit on which money has been spent by enclosing it in a building.

To conclude, the outdoor factory has presented new problems in an age when good lighting is expected as a right in industry of all types. The techniques of lighting are being developed along new lines, involving more careful design and more thorough maintenance, and there is every reason to suppose that the growing use of outdoor factories will be accompanied by improved lighting systems.

For further reading, reference may be made to the technical report on "Lighting in Hazardous and Corrosive Situations", published by the Illuminating Engineering Society.

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SENSATIONS OF WARMTH AND FRESHNESS OF WORKERS IN LIGHT INDUSTRY IN SUMMER*

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Abstract

The paper presents findings from a survey among factory workers during summer months, when measurements were made of the thermal environment, and workers expressed their sensations of warmth and freshness.

A significant relationship was found to exist between the sensations of warmth and of freshness experienced.

The cooling power of the kata-thermometer was shown to be a more adequate index of sensations of freshness than was dry-bulb temperature, under the conditions studied.

Examination of the relationship between air movement and sensations of freshness and stuffiness gave evidence that, with a mean air temperature of 70°F, sensations of "freshness" did not occur unless the air movement exceeded 80 ft/min.

1. INTRODUCTION

IN a field survey carried out during summer months in 6 factories in Southern England, factory workers engaged in light work were interrogated regarding their sensations of warmth and freshness, and at the same time measurements were made of the thermal environments giving rise to these sensations. A total of 2033 subjective sensations of each type was obtained (1537 being from factory workers, and 496 from postal sorters), and 271 assessments of the thermal environment were made.

The results of the analysis of the warmth sensations have already been published (HICKISH, 1955) and the summer comfort zones for workers engaged in tasks described as sedentary or light manual were found to have the values shown in Table 1. (The

TABLE 1. SUMMER COMFORT ZONES FOR WORKERS ENGAGED IN LIGHT ACTIVITY

Thermal index	Optimum condition	Upper limit of comfort zone
Air temperature (°F)	66·8	75
Globe temperature (°F)	68·5	75
Effective temperature (°F)	62·9	70
Corrected effective temperature (°F)	64·4	71
Equivalent temperature (°F)	65·9	73
Dry kata cooling power (100°–95°F)	6·3	4·5

* This paper describes a part of the work approved by the University of London for the award of the Degree of Doctor of Philosophy.

upper limit of the comfort zone was defined as the condition above which less than 80 per cent of persons questioned reported sensations of "comfort".)

The present paper gives some further information regarding warmth sensations in relation to ventilation and building construction, and presents the main findings from the analysis of the freshness sensations.

II. SENSATIONS OF WARMTH IN RELATION TO VENTILATION

The scale of warmth sensations used in the investigation was that of Bedford (1936), the standard sensations being:

Much too warm
Too warm
Comfortably warm*
Comfortable*
Comfortably cool*
Too cool
Much too cool

Those sensations marked with an asterisk were regarded as sensations of comfort, and the others as sensations of discomfort. During the period of the investigation (14 weeks) the external temperature ranged from 46·9°F to 78·7°F.

The internal environment of a factory not equipped with air conditioning will be affected by the external meteorological conditions, by the thermal characteristics of the operations carried on in the factory, and by the construction and ventilation arrangements of the buildings. Two of the 6 factories which were investigated were air conditioned, and one was a multi-storey building of much heavier construction

Table 2. Effect of ventilation of factories upon internal temperatures and percentage of persons thermally comfortable in relation to outside temperature

Mean external temperature (°F)	Typical modern factories Average ventilation		Factory with poor ventilation	
	Mean internal temperature (°F)	"Comfort" votes (%)	Mean internal temperature (°F)	"Comfort" votes (%)
48–	—	—	67·2	96·3
50–	—	—	—	—
52–	—	—	—	—
54–	69·9	77·2	—	—
56–	—	—	—	—
58–	65·8	82·5	66·3	78·9
60–	70·8	89·3	68·0	95·5
62–	70·7	87·6	—	—
64–	68·6	98·6	—	—
66–	70·9	98·5	74·0	60·0
68–	71·0	90·1	—	—
70–	71·6	88·1	75·7	56·3
72–	—	—	—	—
74–	—	—	80·1	13·8

than the others. The results from these 3 factories are excluded from the present analysis. The remaining 3 factories were single-storey buildings, of similar light modern construction, and all the factory processes were comparable in that hot gases and fumes were not evolved, nor were there appreciable sources of radiant heat. The ventilation of one of these factories was poor, as doors and windows were kept closed to prevent contamination of electrical contacts by dirt-laden air from a nearby road and main railway line. In the other 2 factories the ventilation was average.

The adequacy of the internal environments of these latter 3 factories in promoting thermal comfort among the workers may be deduced from Table 2, in which the mean daily internal dry-bulb temperatures and percentages of persons feeling thermally comfortable are shown in relation to the mean daily external dry-bulb temperature measured at 4 ft above ground level.

It will be seen that with average ventilation at least 80 per cent of persons were comfortable over a range of outside conditions from 58°F up to 72°F. In the factory with poor ventilation, there were not more than 60 per cent of persons comfortable at outside temperatures exceeding 66°F. The reason for this is seen in the higher internal temperatures in the poorly-ventilated factory, which on warm days exceed those in the other factories by up to 4°F for the same range of outside temperatures.

III. SENSATIONS OF FRESHNESS IN RELATION TO THE PHYSICAL FACTORS OF THE ENVIRONMENT

(*a*) *Introduction*

If a thermal environment is to give rise to sensations of thermal comfort among the occupants, it is not only necessary that the appropriate heat transfer between the body and the environment should be facilitated, but also that the atmosphere should appear generally pleasant and stimulating, rather than heavy and stuffy. It is generally accepted that the sensations of freshness or stuffiness evoked by an environment will largely be influenced by the degree of thermal stimulation of the exposed areas of skin, particularly of the face, by the environment. In a field study in factories, BEDFORD and WARNER (VERNON *et al.*, 1926) recorded their own sensations of freshness and stuffiness and showed that the degree of sensation of "stuffiness" was largely influenced by differences in air temperature, whereas the degree of "freshness" sensation experienced was due chiefly to differences in air velocity. Some years later they submitted their data to further statistical treatment (BEDFORD and WARNER, 1939) and showed a relationship between average air speed and subjective impressions of freshness, and also between variability of air movement and these impressions, particularly during summer conditions. They found that the kata-thermometer cooling power was as good an environmental index as any of the other variables studied. More recently TURNER (1955) studied the threshold values of air temperature and air movement for sensations of warmth and coolness on the forehead and face, and confirmed that small changes in air temperature and variability of air movement, of insufficient magnitude to influence thermal sensations, may well be sufficient to affect considerably sensations of freshness and stuffiness.

The investigation now being described was intended primarily as an investigation of thermal sensations, whereas the studies referred to above were primarily studies of freshness sensations. However, in the present study, the workers were questioned

regarding their sensations of freshness concurrently with questions regarding sensations of warmth. The scale of freshness sensations used is shown in Table 3, together with the numerical values which were assigned to these sensations for the purpose of statistical analysis.

Table 3. Scale of freshness sensations

Sensation of freshness	Numerical value
Very stuffy	+3
Stuffy	+2
Slightly stuffy	+1
Comfortable	0
Slightly fresh	−1
Fresh	−2
Very fresh	−3

The present investigation differs from that of Vernon and Bedford in that a total of 2033 observations was obtained from approximately 400 work-people not previously trained in assessing freshness, whereas the earlier investigators obtained only 229 observations during summer months, representing the opinions of 2 trained observers.

(b) *The correlation of freshness sensations with warmth sensations*

The relationship between sensations of warmth and of freshness expressed simultaneously by the same individuals is shown in Fig. 1, from which it can be seen that the relationship between mean freshness vote and mean warmth vote is substantially linear, corresponding to the equation:

$$y = 0{\cdot}639\,x + 0{\cdot}222$$

where

$$y = \text{mean freshness vote}$$

$$x = \text{mean warmth vote.}$$

The correlation coefficient is 0·617 and the standard error of estimate of freshness vote from warmth vote is 0·806.

It appears, therefore, in the present investigation that, under the conditions observed, which were mainly warm rather than cool, there was a definite relationship between freshness and warmth sensations.

(c) *The kata-thermometer cooling power as an index of freshness*

The earlier analysis of the warmth sensations showed the kata-thermometer cooling power to be inferior to dry-bulb temperature, globe temperature, corrected effective temperature and equivalent temperature as an index of warmth sensations. Cooling power might, however, be expected to be more useful as an index of freshness sensations, and this possibility has been examined by comparing the relationships of dry-bulb temperature and cooling power to the mean freshness votes expressed by the factory workers. The relationship with dry-bulb temperature is shown in Fig. 2, from which it will be seen that a discontinuity occurs at about 75°F. A similar discontinuity occurring in the relationship between dry-bulb temperature and mean

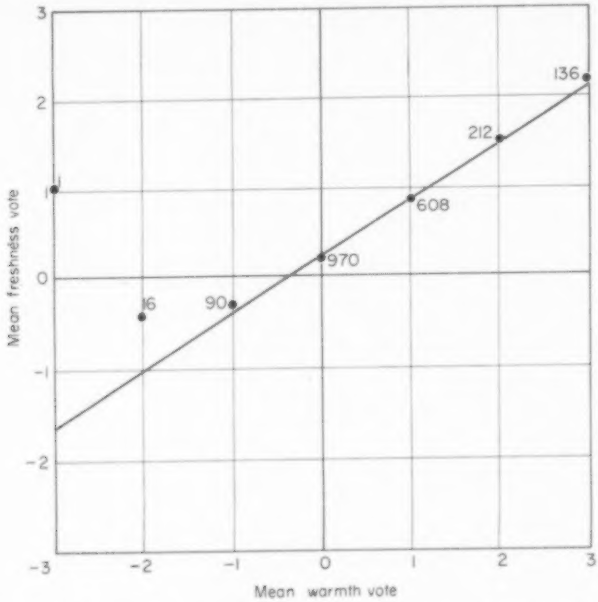

FIG. 1. The relationship between freshness sensations and warmth sensations. (Positive values of the mean freshness vote indicate sensations of "stuffiness".)

Note: The small numbers indicate the number of observations represented by each point.

warmth vote was attributed to the onset of sweating beneath the clothing, and the discontinuity in Fig. 2 is probably related to this effect.

For the purposes of the comparison, the observations used are those comprising the linear portion of Fig. 2, and the corresponding relationship between mean freshness vote and cooling power is shown in Fig. 3. The regression data relating to Figs. 2 and 3 are shown in Table 4.

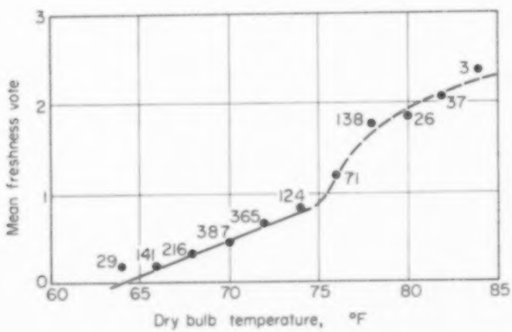

FIG. 2. The relationship of the freshness votes of factory workers to dry-bulb temperature.

Note: The small numbers indicate the number of observations represented by each point.

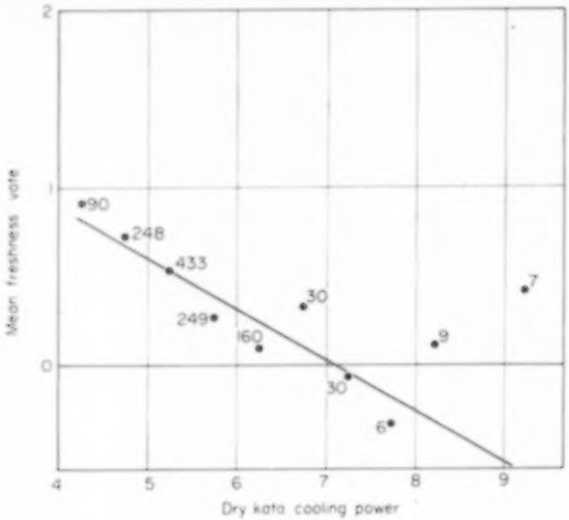

Fig. 3. The relationship of the freshness votes of factory workers to dry kata-thermometer cooling power.

Note: The small numbers indicate the number of observations represented by each point.

Table 4. Regression data relating to freshness votes, dry-bulb temperature and kata-thermometer cooling power

Variable	Freshness vote correlated with	
	Dry-bulb temperature	Cooling power
Range	63·0 to 74·9°F	4·0 to 9·45
Mean	70·0°F	5·44
Standard deviation	2·46°F	0·77
Correlation coefficient	0·21	−0·24
Regression coefficient	0·078	−0·29
Constant	−4·99	+2·05
S.D. of freshness vote	0·925	0·925
S.E. of estimate	0·904	0·872

(d) The influence of air movement on sensations of freshness

The freshness sensations of the factory workers in relation to air movement are shown in Fig. 4. The data used are those corresponding to air temperatures not exceeding 74·9°F, the temperature at which a discontinuity was observed in the linear relationship between air temperature and sensations of freshness.

Two high velocities in the groups 170— and 230— did not appear to fit the rest of the data, and the reason for this is probably that these two results represented a local high velocity (such as could arise from the partial opening of a door), which was

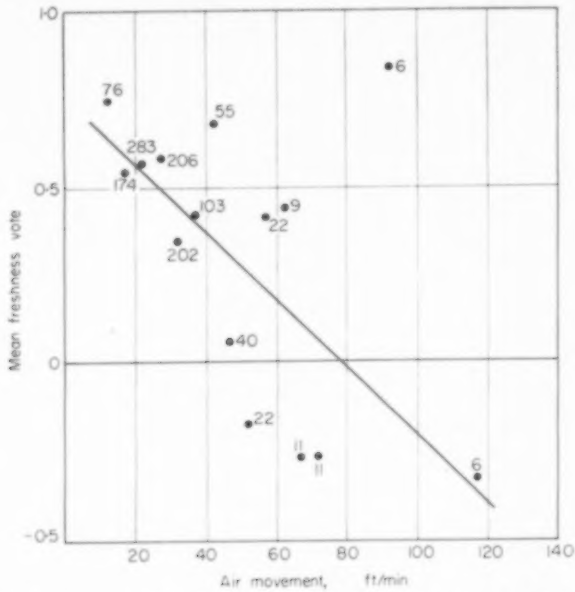

FIG. 4. The relationship of the freshness votes of factory workers to air movement.
Note: The small numbers indicate the number of observations represented by each point.

measured by the instruments but was not experienced by the workers situated a short distance away. These two observations if included would unduly affect the regression analysis, and they have therefore been omitted from the analysis, reducing the number of observations to 1246. The correlation coefficient between sensations of freshness and air velocity is $-0{\cdot}144$ (S.E. $= 0{\cdot}028$), and regression analysis gives the equation:

$$y = 0{\cdot}00966\,x + 0{\cdot}759$$

where y = mean freshness sensation

x = air velocity, in ft/min.

It is possible that a relationship may exist between air temperature (which has been shown to be related to sensations of freshness) and air movement, and this has been investigated. For the range of air movements and dry-bulb temperatures represented by the data selected above (i.e. excluding the two high air velocities, and using only the range of air temperature over which a linear relationship with freshness sensations exists), the correlation coefficient, r, is 0·017 which is not statistically significant (S.E. of $r = 0{\cdot}074$). There is thus no evidence of any correlation between air velocity and air temperature, and the observed relationship between sensations of freshness and air movement may be considered independently of air temperature.

(*e*) *Discussion*

When the relationship between the warmth votes and freshness votes expressed simultaneously by individuals is examined, a marked correlation is found. There appear to be two possible reasons for this. The subjects involved in the investigation were not specially trained observers (as were VERNON, BEDFORD and WARNER) and

they probably had some difficulty in differentiating between the two types of sensation.

Alternatively, or additionally, the cause of this relationship may be found in the fact that the conditions encountered were such as to give rise to feelings on the "stuffy" side of the freshness scale. It will be remembered that VERNON *et al.* showed that in this zone the freshness sensations are closely related to air temperature. It has been shown previously by BEDFORD that warmth sensations also are closely correlated with air temperature. Thus as both warmth and freshness sensations are related to a common variable, an inter-sensation relationship is to be expected, and has in fact been shown to exist.

Under the conditions encountered in which the mean air movement was 31·5 ft/min (S.D. = 20 ft/min) there is evidence that the kata-thermometer cooling power is a better index of freshness than dry-bulb temperature, as it is seen from Table 4 that the S.E. of estimate of freshness is lower for cooling power (0·872) than for air temperature (0·904). However, the kata appears to predict freshness with less accuracy than it predicts warmth, as the S.E.s of estimate are 0·872 and 0·808 respectively. Sensations of freshness can in fact be predicted as accurately from expressed sensations of warmth (S.E. of estimate = 0·806) as from kata-thermometer cooling power. It is not suggested, however, that air velocity may be ignored when investigating the adequacy of a thermal environment from the aspect of freshness, as air movement has been shown to have a significant effect upon freshness sensations.

BAETJER (1924) studied the minimum air movements perceptible on the cheek of a single subject and showed that at 70°F (the mean value of the air temperatures relative to the data of Fig. 4) this minimum value was 47 ft/min. From Fig. 4 it will be observed that the factory workers did not begin to experience sensations on the "fresh" side of the neutral sensation until the air velocity exceeded 80 ft/min. For the whole of the series of field observations, the mean value of air movement was 31·5 ft/min with a standard deviation of 20 ft/min. The majority of the observed air movements, therefore, were below (31·5 + 2 standard deviations), i.e. below 71·5 ft/min, and were thus less than the minimum value of 80 ft/min required to give rise to any definite feelings of freshness. From the practical point of view, there is thus further evidence that, during summer weather, the air velocities occurring in typical modern factories are generally inadequate, and are a cause of feelings of stuffiness. Comparison of the data from which Figs. 2 and 4 are derived shows that in terms of the change in sensation of freshness produced, an increase in air velocity of 103·5 ft/min is equivalent to a reduction in air temperature of 12·8°F. The value of increasing air movement as a remedy for complaints of stuffiness is thus apparent. The author, in common, no doubt, with many of his readers, has had several experiences of situations where complaints of stuffiness in offices and workshops have largely been overcome by the simple expedient of utilizing existing unit-heater fans as sources of air movement.

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DISCRIMINATION BETWEEN ROCK AND COAL PARTICLES IN THERMAL PRECIPITATOR SAMPLES OF RESPIRABLE DUST

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Abstract

A review is made of the various possible methods for discriminating between rock and coal particles in thermal precipitator samples of respirable dust. Two methods are described in detail: an incineration method for use in conjunction with a densitometric evaluation, and a microscopical technique using modified dark-field illumination. The validity of the two methods is tested, and their relative advantages outlined.

Supporting experiments are described on the behaviour of rock particles and coal particles during incineration, with particular reference to the suspected fragmentation of rock particles and to the disturbing effects of ash residues from coal particles.

INTRODUCTION

THE composition as well as the quantity of dust breathed is of importance in the causation of coal miners' pneumoconiosis, but so far comparatively little attention has been given to this factor in routine airborne dust sampling procedures in Britain.

Differences are already recognized between coal dust clouds in anthracite and in other collieries, and between these and dust clouds in stone drifts and hard headings. When allowance is made for differences in particle size as well as in concentration it appears that stone dust is rated to be about six times more dangerous than coal dust. No intermediate standard between these widely separated extremes is recognized, however, for application to the many working places in a colliery where mixed dusts are found. This has given rise to differences of interpretation in practice. The situation requires that weight should be given to the relative amounts of stone and coal in a mixed dust cloud.

This paper reviews methods of discrimination, suitable for routine application. The aim has been a broad discrimination between coal and stone and not a more detailed determination of individual mineral constituents.

SURVEY OF METHODS FOR ANALYSING DUSTS INTO THEIR MINERAL COMPONENTS

Chemical methods

The great handicap of chemical methods is the amount of material, usually of the order of a gram, that they require. Such amounts entail special sampling techniques for airborne dust. In addition, only a bulk estimate is made of the non-coal content, no clue as to particle sizes being obtained. Further, chemical methods are long and

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tedious, an analysis taking usually about 12 to 24 hr to perform, although several analyses may be run in parallel. DURKAN's method (1946) involves treating the sample with hydrochloric acid, phosphoric acid and hydrofluoric acid in succession. A variant of this method, in which only 10 mg of dust are needed, has been developed (BLANZAT and BARBE, 1953) and corrections are made for the solubility of free silica in hydrofluoric acid. TALVITIE's modification (1951) of the Durkan method aims at reducing the interference from the silicate materials.

X-ray diffraction

This, again, gives a bulk estimate of the mineral composition of a dust sample without direct reference to particle sizes; unfortunately coal itself scatters X-rays over a region where most other minerals have strong diffraction lines (RAY *et al.*, 1951).

Geiger–Müller counter diffractometry is now used for such work, with artificially-compounded dust mixtures of known composition as reference standards (GORDON and HARRIS, 1957). Analyses of more than 100 samples per week can be made on a single instrument. Fractions of a gram of sample are needed, calling for gravimetric collection equipment if respirable fractions only are to be assessed, although analyses have been made exceptionally on samples of a few milligrams weight only. It has been concluded that the results of routine determinations of quartz content may be accurate to 4 per cent.

Density methods

The density of rock being about twice that of coal provides a basis for separating the two by sedimentation. In order to separate the two components, it would be necessary to suspend the dust in a fluid having a density midway between rock and coal. The falling speed of a 1μ particle is of the order of 10^{-4} cm/sec, so that 10^{5} sec (30 hr) are needed for a fall of 10 cm. At small particle-sizes Brownian movement becomes important and tends to keep the particles in suspension. The process may be accelerated by using a high-speed centrifuge and complete analysis made in a few minutes on sizes down to $0{\cdot}05\ \mu$, using centrifuging speeds of 4000 rev/min (WHITBY, 1955).

Microscope methods

Immersion method. For particles greater than 5μ it is a relatively simple matter to distinguish rock particles from coal particles by their general appearance under a microscope. With particles less than $5\ \mu$ this discrimination is by no means simple. Resort can alternatively be made to special microscope methods. Quartz, for example, has a refractive index of $1{\cdot}54$, and by immersing a sample containing quartz in a medium of refractive index close to this value it is possible to pick out this component. When the medium has a refractive index slightly below that of quartz and the microscope objective is raised slightly above focus the quartz particles appear to have bright centres. On the other hand, when the medium has the higher refractive index the particles have dark centres. It is impossible by this means to deal with particles smaller than about 2μ or to discriminate between quartz and any other of the clay minerals that may be present.

A more promising technique is provided by a combination of dispersion staining with dark-field illumination (CROSSMAN, 1949). Here the dust is immersed in a fluid having a large optical dispersion. The dispersion curves for the immersion medium and for the particles under investigation intercept at wavelengths depending upon the mineral composition of the particles. Thus, quartz may appear blue and kaolinite red. A lower limit for this method has been fixed at 2 μ, but may be reduced by phase contrast. A typical embedding medium is a mixture of diethylene glycol monobutyl ether and cinnamaldehyde. The writer has experimented with this technique on thermal precipitator samples but has not had the success claimed for it on konimeter samples (THAER, 1954). One of the main sources of trouble was movement of the dust as soon as the immersion liquid was added. To give a reasonable concentration after dispersion it is necessary to take an extremely heavy sample, about 30 times denser than usual, but this disadvantage may be overcome to a certain extent by using membrane filters as samplers. These filters are made of cellulose acetate and are soluble in many organic solvents. It is, however, difficult to prevent aggregation when an optically dispersive medium is used instead of the more usual solvents. Moreover, it is the author's experience that the coal itself exhibits colours when viewed under these conditions, and so a system that discriminates successfully between the different constituents of a rock sample breaks down when coal is present.

Viewing by polarized light. Quartz and the other clay minerals comprising sedimentary rocks are nearly all birefringent but, as compared with calcite, for example, the birefringence is very weak. Counting rock particles under crossed nicols with a 2 mm oil-immersion objective has been attempted and for pure rock is quite successful. When coal is added, however, it is almost impossible to distinguish between the two kinds of particle below about 5 μ. This is probably due in part to the fact that the coal particles contain small rock inclusions, which make the coal particles appear birefringent when they are near the surface. This matter is dealt with more fully later and the effect is illustrated in Fig. 1. A formula due to Fresnel shows that difficulties in discrimination on the basis of birefringence are to be expected.

The intensity I transmitted by a birefringent particle illuminated with intensity I_0 and viewed through crossed nicols is

$$I = I_0 \sin^2 2\varphi \sin^2 \left(\frac{\pi l \Delta n}{\lambda}\right)$$

where Δn = birefringence
λ = wavelength of light in air
l = thickness of particle
φ = angle between the plane of polarization of the incident light and the crystal axis.

It follows that I will be a maximum when $\varphi = 45°$ and zero when $\varphi = 0°$. For quartz, the refractive indices are 1·553 and 1·544, so that $\Delta n = 0{\cdot}009$.

Hence, for a 1 μ particle, $I = I_0 \times 0{\cdot}003$ at most, and, for a 5 μ particle, $I = I_0 \times 0{\cdot}075$ at most.

The brightnesses of the smaller respirable quartz particles arising from birefringence are therefore very low and the particles would not be readily distinguishable from other small particles showing no birefringence.

The colours that birefringent quartz particles assume under polarized light conditions have also been studied (THAER, 1955) but the variations are insufficient to lead to a method of discrimination between rock and coal particles.

Incineration

Apart from their differences in density, the most obvious property in which coal and rock differ is that of combustibility. Pure carbon, when heated in air, disappears without trace, whilst rock, being incombustible, remains virtually unchanged. Unfortunately, coal leaves a residue, and it is therefore necessary to provide a correction when estimating the rock content of mixed samples by incineration in combination with particle counting. The success of this method depends upon how accurately the ash content can be predicted, upon whether it differs for different kinds of coal, and, what is more important, upon whether it fluctuates for different samples of coal taken from the same location. One other important factor to be decided is whether rock does in fact remain unchanged upon heating. All these factors will be considered in some detail. As will be shown later, the incineration technique can be modified by shadowing the specimen before treatment, and densitometry can be substituted for normal counting.

Other methods

Some success has been obtained with colorimetric methods (BANNERJEE and COLLIS, 1955), but once again a bulk estimate is made of the different mineral components. A possible feature of rock and coal dusts that could be used to differentiate between them is their differing size distribution. Drilling processes in the laboratory show a distribution function of the form $1/_{D}\beta$ (HAMILTON and KNIGHT, 1958), where values of β vary from 2·25 to 2·32 for coal and 2·72 and 3·09 for rock. These figures do not differ sufficiently. Recent tests on underground samples show a variation in the ratio of the ($\frac{1}{2}$ to 5 μ) count to the (1 to 5 μ) count of about 6 to 1, suggesting that underground samples are subject to random variations of size distribution. These variations may be due in part to atmospheric pollution.

METHODS STUDIED FOR DISCRIMINATION BETWEEN ROCK AND COAL PARTICLES IN THERMAL PRECIPITATOR SAMPLES

It follows from the above that a technique is required to investigate the dusts in the dispersed particulate form obtaining in current sampling methods rather than in bulk. Work has been largely confined to techniques involving incineration, although a little effort has been diverted to a novel microscopical approach.

Discrimination by incineration

At best, this method can only distinguish between the combustible and the incombustible fractions; however, as the major part of incombustible underground dust is rock, the technique may be said to distinguish between rock and coal.

Effect of incineration on airborne rock particles. The first experiments were directed towards establishing the constancy of various rocks under heat. Photographs were taken on a Vickers projection microscope of ordinary thermal precipitator coverslips coated with three representative rock dusts, these being Darley Dale Sandstone,

Pennant Sandstone and a fine-grained quartzitic sandstone, obtained from the coal measures of the Petal opencast site, Heanor, Derbyshire, described as "Petal Sandstone". The samples were then heated in air in a small oven to a temperature of 550°C for times extending up to 4 hr. A new set of photographs was then taken of the same fields as before. A low magnification was first used, as it was suspected that if any particles shattered under heat they would most probably be the larger ones. Further exposures were made at the limiting magnification of the equipment and in neither case was disintegration upon heating observed. It has been said from time to time that various shales were unstable on heating, considerable breaking-up of the particles occurring. One of these suspect shales was obtained from Madeley Wood Colliery and similar tests carried out. As with the hard rocks, no break-up of the particles took place. It would appear, therefore, that one of the principal requirements of an incineration technique is fulfilled.

Effect of incineration on airborne coal particles. Attention was then turned to the effect of heat upon coal. Fig. 1 shows a "Rawdon" coal before and after incineration. Coal, being combustible, is considerably changed after heating and it is impossible to recognize corresponding fields before and after incineration. A reference scratch was therefore made on the coverslip. To be completely confident of the location, the original negative of the field before incineration was placed on the projection screen, and a check made to see that all the ash particles had been originally covered with coal.

It is apparent from these photographs that on a particle count basis coal leaves a considerable residue after incineration. The photographs taken with crossed nicols before and after incineration show that coal particles exhibit birefringence, and some birefringent particles survive incineration. This suggests that these particles are rock inclusions within the coal.

The question arises, whether coal particles with rock inclusions should be placed in the "rock" or the "coal" category in the present work, which tries to separate dust particles into two classes only. The question will be answerable only when the roles of the various particles in the causation of pneumoconiosis are established. For the present it is assumed that only rock particles should appear in one class while both coal particles and coal particles with rock inclusions should appear in the other.

A further question that has been asked is how many of the so-called rock particles visible in the coal ash are the products of more finely dispersed clay minerals, scattered throughout the coal particles, which fused together when the coal particles burnt. To investigate the problem, a previously incinerated coal specimen was overlaid with anthracite dust, making certain that some of the old ash particles were covered by new coal ones. The sample was incinerated again. Any fresh supply of heat should cause refusion of the old ash particles with some of the new ash formed by burning the coal. But, as can be seen from Fig. 2, this has not happened, and the particles numbered 1, 2, 3 and 4 preserve their original identity.

Accepting that coal leaves a residue, the next step was to see whether it could be allowed for in counting from a knowledge of the amount and nature of the coal dust originally present. If it could be shown that particles of a particular coal consistently left a certain proportion of ash particles after incineration, it would be possible to determine the rock fraction in a given sample of dust by counting particles before and after incineration and making due allowance for the known ash residues. How-

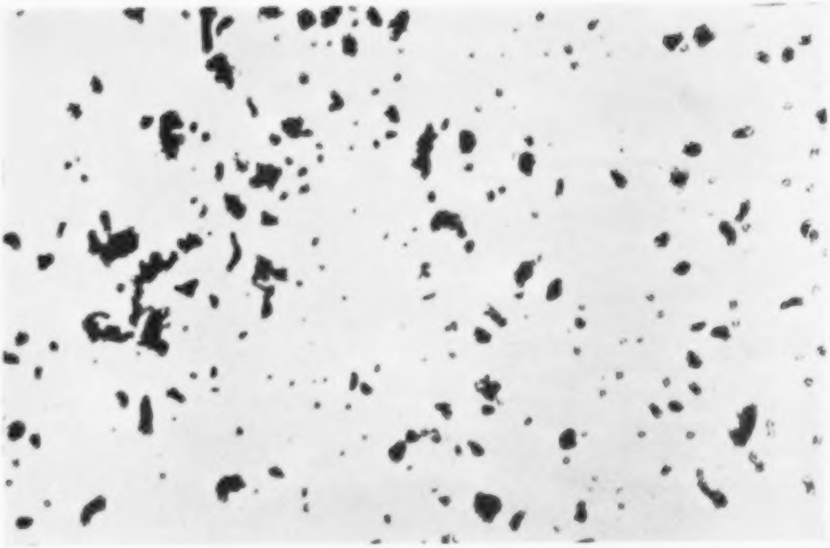

FIG. 1(a). Rawdon coal dust particles viewed with transmitted light and with crossed nicols successively before incineration (Field width 200 μ).

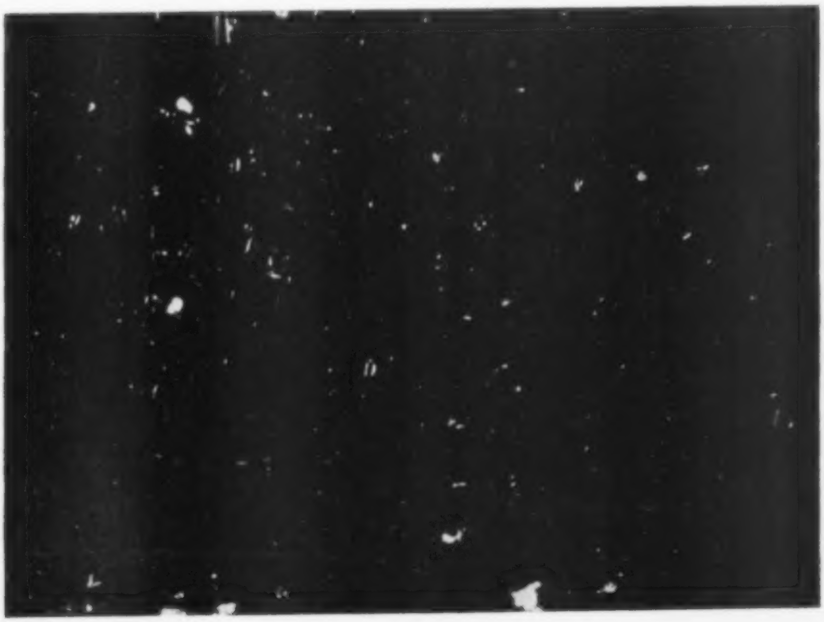

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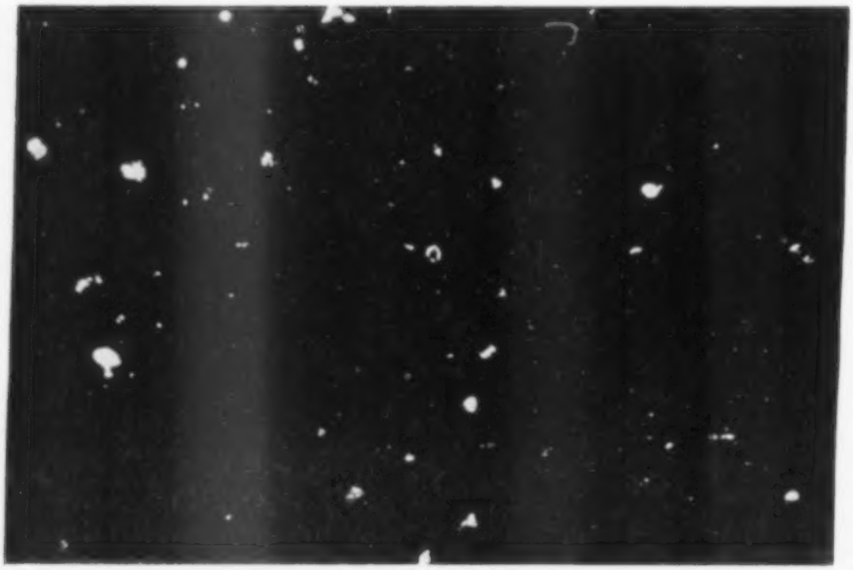
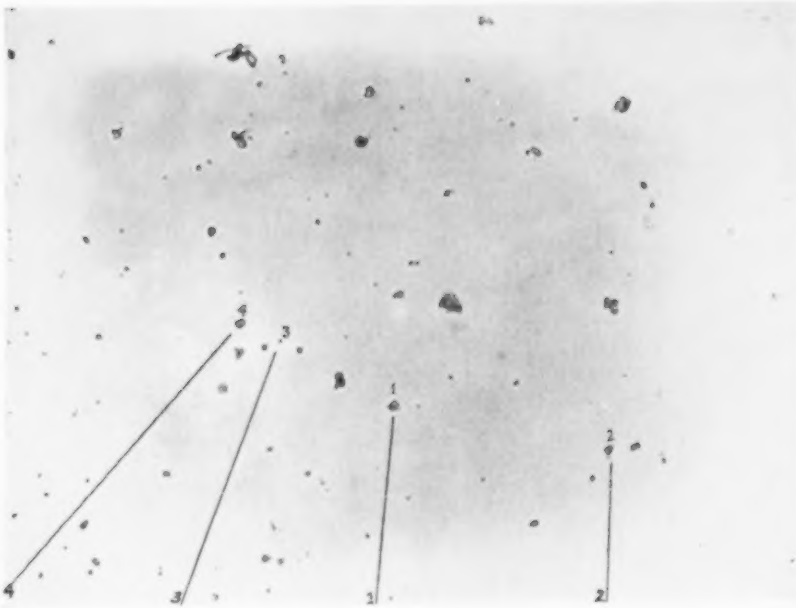
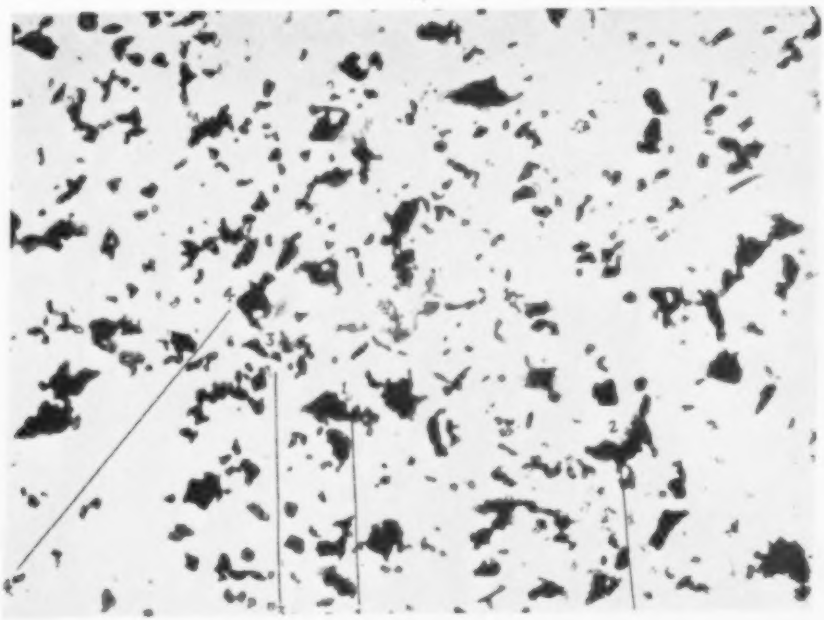
FIG. 1(b). The same after incineration for 1 hr at 550°C (Field width 200 μ).





(a)



(b)

FIG. 2. Test on possibility of fusion of ash residues.

(a) Ash residue from incineration of Barnsley Bright coal dust particles (Field width 200 μ)

(b) Residual ash overlaid by anthracite (Field width 200 μ)

FIG. 2 (c). After incineration of the overlying anthracite (Field width 200 μ).

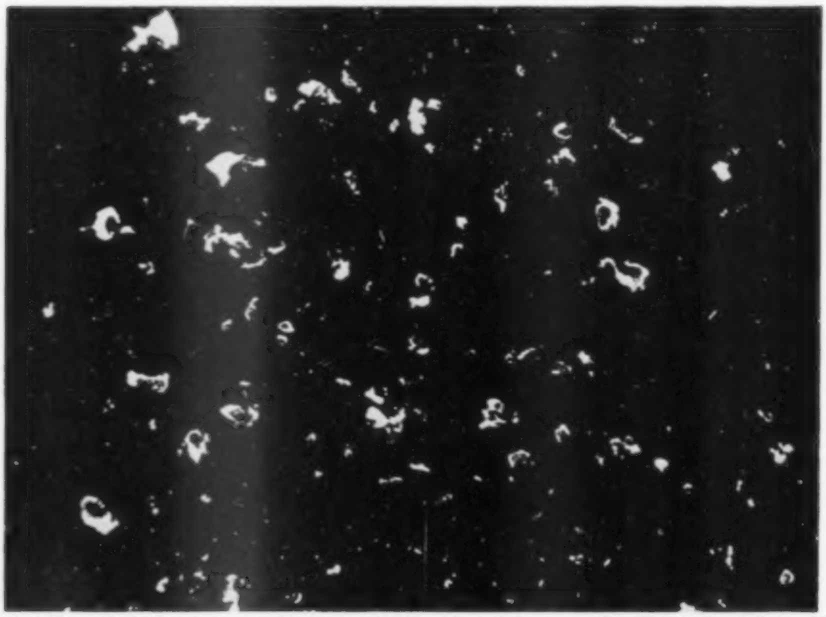


FIG. 3. Effect of incineration on aluminium shadowed coal dust samples. Transmitted light (Field width 200 μ).

ever, wide variations in the number of ash particles left on incinerating coal particles were apparent, even among dust samples taken from separate lumps of coal from the same location. Any attempt to allow for the ash content on the basis of previously determined ash residues would therefore be subject to large errors, and it became clear that it would not be possible to assess the proportion of rock particles in a mixed dust sample by simple microscopical counting before and after incineration.

Appraisals of two variations of the simple incineration method are described in the following paragraphs.

Incineration of aluminium-shadowed samples

If an aluminium film is evaporated on to a mixed rock and coal dust deposit, the film will preserve the initial outlines of the dust particles (HAMILTON and PHELPS, 1956). After incineration, various fractions of the coal particles will have disappeared, leaving holes in the original film, whereas rock particles and their corresponding shadows will remain unchanged (Fig. 3). However, the difficulty remains in deciding whether a particular feature under 5 μ in diameter is a hole in the coating or a transparent rock particle. Also, under heat the aluminium film tends to oxidize and to become transparent, and at temperatures of about 450°C the effect is accelerated. As only the bituminous coals burn below this temperature care must be exercised in ensuring that the opacity of the film is not completely lost during the incineration process. Various other metals were tried as coatings but none appeared to be as reliable as aluminium. The critical test is the lower size limit at which discrimination may be made with confidence, and this is certainly not much below 5 μ.

Incineration in conjunction with densitometry

It has been shown that the residual ash left on burning coal particles vitiates any estimation of rock fractions when visual counts are made on the particles in the different size ranges before and after incineration. However, it was observed that the ash particles remaining after incineration were always smaller in size than the original coal particles, and, moreover, they appeared to be more transparent than rock particles of comparable size.

A method capable of utilizing these two effects is that developed for "counting" the dust particles in long-running thermal precipitator samples (HAMILTON, 1958) by means of a specially designed photoelectric densitometer (BUGDEN *et al.*). This differs from the instrument described by THAER (1958) in which scattered light is used as a measure of particle concentration. The slides are scanned by a beam of light of small solid angle. The beam is focused on the slide in a patch 1 mm in breadth and covering the whole width of the dust deposit in a direction parallel to that occupied by the hot wire in the long-running thermal precipitator itself. The optical density at a particular part of the dust deposit is proportional to the concentration of the (greater than 1μ) dust particles there, and calibration curves have been determined for traverses across deposits of dust from various coals and rocks by comparisons with microscopical counting. Within experimental error, the calibration curves are all of one shape, but the conversion factors between optical density and particle count differ by $\pm$15 per cent of the mean according to the nature of the dust, sandstone and soft coal appearing at the extremes. Since the nature of the dust samples will be unknown

in work calling for discrimination, a mean calibration curve based on determinations for rock, coal and dirt band is used here.

The procedure in determining the rock fraction in a particular dust sample was then simply to determine the number of particles in the specimen by means of the densitometer before and after incineration. The ratio of the final densitometer count to the original densitometer count gives the required fraction of rock.

In order to test the accuracy of this method two separate densitometer counts were made before incineration; one of a rock deposit *per se* and another after overlaying this deposit with one of coal. A third count was made after incineration. The first count may be regarded as the true amount of rock present in the mixed sample and the third an estimate of the amount of rock but now modified by the ash left from the coal.

The percentage of rock introduced varied in the experiments between 30 and 70 per cent. The reliability of the method is determined by the divergence between the first and third counts. The results for Darley Dale Sandstone overlaid with Rawdon coal are shown in Table 1. Three distinct parts of the deposited dust trace were measured separately, viz, the thermal precipitation zone, the central region, and the coarse end, so that any effects due to the different particle size distribution characteristics of rock and coal dust clouds could be observed. The table shows the mean errors of the determined fractions of rock by count, together with the standard deviation of the individual errors from the mean, on the basis that the fraction determined by the overlay process before incineration is accepted as correct. The differences are not significant at the 5 per cent level of probability.

Table 2 shows the fractions of rock by count obtained in this way from samples of each of the following three mixtures of rock and coal dust particles:

(1) Darley Dale sandstone and Rawdon coal,
(2) Petal sandstone and Pentremawr anthracite,
(3) Pennant sandstone and Barnsley Brights.

Some of the results for the first combination have already been used in the production of Table 1, but the analysis is now extended to give the densitometer counts for the sample as a whole. The greatest weight in the overall counts arises from the thermal precipitation zone, and the results from that zone are therefore still shown separately in Table 2. Critical comparisons may then be made with the total estimate from all zones on which the determination of the fractions of rock by count would normally be based.

TABLE 1. FRACTION OF ROCK BY COUNT DENSITOMETRY AND INCINERATION

The mean error and standard deviation between the true amount of rock as determined by the densitometer count before overlaying with coal and the estimated amount obtained by densitometer counting after incineration. Darley Dale Sandstone and Rawdon Coal—results from eight samples.

Thermal precipitation zone	Central region	Coarse end
0·01 ±0·03	0·03 ±0·05	0·04 ±0·06

TABLE 2

As Table 1 but extended now to eight samples of each of three rock/coal mixtures in thermal precipitation areas of samples and over complete deposition areas.

	Darley Dale Sandstone and Rawdon Coal	Petal Sandstone and Pentremawr Anthracite	Pennant Sandstone and Barnsley Brights
Thermal deposition area	0·01 ±0·03	0·00 ±0·04	0·07 ±0·05
Whole deposition area	0·01 ±0·02	0·01 ±0·03	0·05 ±0·05
Overall mean error and standard deviation	0·02 ±0·04		

The errors and standard deviations shown in Tables 1 and 2 show that in only one case, the Pennant Sandstone/Barnsley Bright combination, are the errors significantly different from zero, taking the 5 per cent level of probability as the criterion.

The overall mean error in the determination of the fractions of rock by count in the 24 samples, comprising 8 of each of 3 rock/coal mixtures, and on the basis of densitometer counts in the whole deposition area, is 0·02, with a standard deviation of individual determinations from the mean of 0·04 (Table 2). This accuracy is fully adequate for present purposes.

Discrimination by a microscopical method

For identification of individual particles a microscope method is essential. Discrimination between particles greater than 5μ is straightforward in terms of their different transparencies, but for particles less than 5μ this becomes progressively more difficult as the particle size is reduced. Under certain conditions a modification of dark-field illumination has been found to aid recognition considerably.

With a microscope set up for use under dark-ground illumination conditions and using a condenser of the cardioid reflector type it is necessary to remove the front element of the condenser if immersion oil is not used between the condenser and cover slip (light emerging from the last element is at so oblique an angle that total reflection occurs at the glass-air interface). However, it was found that by keeping the illuminator intact and moving it closer to the cover slip a mixture of transmitted and dark-ground illumination resulted. What probably happens is that some light is scattered from the edges of the condenser and produces a ring of light close to the plane of the specimen, and in fact an image of this ring may be seen formed by the objective. The net result is that rock particles are highlighted with respect to coal particles. A further improvement in discrimination may be achieved by coating the deposit with paraffin oil (kerosene). After adding one drop to the deposit the sample is heated for about 15 min at a temperature of about 60°C. This seems to remove the more readily evaporated fractions in the oil and to leave a thin film coating the particles, and this would appear to modify the transmission through the rock *vis-à-vis* the coal

in such a way as to improve further the discrimination between the two components (Fig. 4).

A suggestion for an essentially similar method, in which coal particles appear dark in bright-field illumination, and rock particles appear bright simultaneously by dark-field illumination, has also been recorded by THAER (1957).

A number of traverses on a set of three ordinary thermal precipitator samples of airborne Darley Dale sandstone rock dust were first counted in the normal manner in the ($\frac{1}{2}$–5 μ) size range for their rock particle content and the samples were then overlaid in the precipitator with Rawdon coal dust and the same traverses recounted, again in the ($\frac{1}{2}$–5 μ) size range, so that the rock and coal counts in the mixture were known. The samples were then treated with paraffin oil, as described earlier, and recounted for both rock and coal contents by visual discrimination under the microscopical conditions defined above. The results shown in Table 3 were obtained by two independent observers. An analysis of variance shows the random variations to be such that no significance should be attached at the 10 per cent level of probability to the apparent differences between the two observers in their determinations of the fractions of rock by count. Similarly, the mean error in the determined fraction of rock by count as determined by microscopical discrimination cannot be regarded as significantly different from zero at the 10 per cent level of probability.

TABLE 3. FRACTION OF ROCK BY COUNT MICROSCOPICAL DISCRIMINATION

The mean errors and standard deviation between the microscopical counts of rock particles before overlay with coal and the count of rock particles in the overlaid sample by microscopical discrimination as measured by two operators. Results from twenty measurements. Darley Dale Sandstone and Rawdon Coal.

Operator 1	Operator 2
0·05 ±0·11	0·00 ±0·09
Overall mean error and standard deviation 0·03 ±0·10	

A more precise check was then made on a marked slide to ensure that successive counts were made on the same field. A cross scratched on the coverslip served as a reference point to locate the various fields. The results are shown *in extenso* in Table 4. The precision is considerably increased, and statistical analysis now shows that the mean error in the determined fraction of rock by count is significantly different from zero at the 1 per cent level of probability but not at the 0·1 per cent level. The mean error, however, is only +0·06, and this may well be attributable to the inclusion in the coal particles of a few rock particles. These would tend to be classed as rock and the rock fraction, as evaluated by the discrimination method, would be artificially increased.

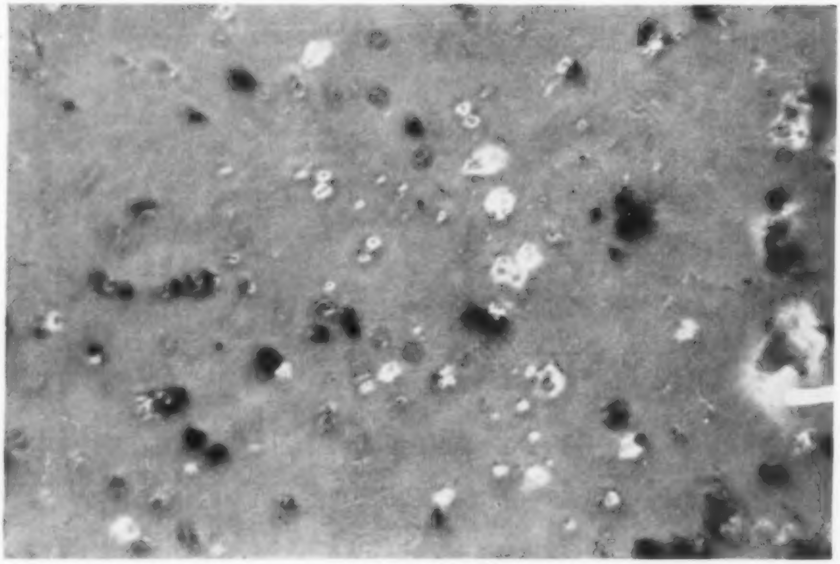


FIG. 4. Discrimination by microscopical method between Darley Dale Sandstone and Rawdon Coal dust particles (Field width 100 μ). Paraffin oil was used.

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TABLE 4. FRACTION OF ROCK BY COUNT MICROSCOPICAL DISCRIMINATION

The microscopical count of rock particles (a) before overlaying with coal and (b) by microscopical discrimination. The counts are normalized with respect to the microscopical count of rock plus coal. Darley Dale Sandstone and Rawdon Coal.

Rock alone	Rock + coal	Fraction of rock in mixture by microscopical discrimination
0·49	1·00	0·53
0·39	1·00	0·56
0·46	1·00	0·56
0·51	1·00	0·57
0·45	1·00	0·53
0·44	1·00	0·48
0·51	1·00	0·50
0·47	1·00	0·53
0·45	1·00	0·47
0·46	1·00	0·49
A		B

Mean error and standard deviation of individual errors in fraction of rock by count
0·06
±0·05
(B−A)

CONCLUSIONS

Two main methods have been found successful in discriminating between rock and coal particles (or, more correctly in one method, between coal and non-coal material) in laboratory-prepared thermal precipitator samples. The microscopical method would be used only in work where detailed investigation of particles is necessary, e.g. to determine whether a given particle is a mixture of rock and coal and, if so, how much of its surface is rock. The technique is inadequately specified for general use. Particles smaller than 1μ can be assessed with considerable confidence, and the lower limit is probably in the region of $\frac{1}{2}\ \mu$.

The incineration method with densitometer counting is much simpler, and lends itself more readily to routine analysis where estimates of concentration are wanted on a comparatively large scale.

Acknowledgements—The writer would like to record the help given throughout the above work by Miss P. M. T. MILES in counting and collecting the samples.

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THE INFLUENCE OF A CHANGE IN PRODUCTION TECHNOLOGY ON THE INCIDENCE OF RADIATION HAZARDS

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INTRODUCTION

THE rapid growth of the number of radioactive workplaces as well as newly originated applications engaged the attention of our health physics division. The risks occurring in work-places that have existed for several decades were not under-valued, but because of their relative knowledge it was assumed that recommendations applied to the latest techniques were quite satisfactory. The present paper shows, however, that radiation hazards to people working with radioluminous substances were in existence.

Radioactive workplaces differ in many ways. One of these, which is often neglected, is the question whether the work with radioactive substances is a central point of interest or whether it represents only one subordinate link in a chain of complicated production processes. In the latter case, people working with radioactive substances are apt to underrate the value of their own problems to the problems of the rest of production and prosperity. Unfortunately, this psychological outlook is rather common even with supervisors, this fact being the more harmful. For these reasons it is desirable to have a permanent and highly intensive supervision enabling us to get control of changes in technology of work; this fact, however, may seem to the workers and operation supervisors to be of small importance with regard to the rise of potential lesions. The health physicist, therefore, should necessarily be a person with a fair knowledge of radiation who has experience of persons working with radioactive materials so that he will be competent to design and approve laboratory and production processes.

TYPE AND OCCURRENCE OF HAZARDS INVOLVED

From the point of view of recent experience hazards included in work with radioluminous paints appear to be

(1) external exposure to gamma and beta radiation
(2) contamination
- (*a*) skin contamination
- (*b*) internal contamination
  - (i) cutaneous (with potential absorption)
  - (ii) oral (e.g. hand–mouth)
  - (iii) inhalation of gases and radioactive aerosols

(3) spread of activity difficult to account for.

The existing recommendations concerning the arrangement of workplaces and procedures of the work with radioluminous substances were made with regard to

^{226}Ra. The increasing claims on the luminosity of the luminous substances necessitated changes in composition, so that the radioluminous substances that are used nowadays are enriched with ^{90}Sr. Table 1 shows some typical formulations as given by the manufacturer, fa. Zeller (Switzerland).

In connexion with this change in composition and with increased production some defects had arisen in these workplaces, these defects being signalled by the occurrence of one case of the radiodermatitis on the back of the fingers of the right hand of a woman applying radioluminous paint; the injury was due to inadmissibly high doses of beta radiation. Health physical investigations in a great number of similar workplaces has shown that the hazards (2) and (3) are the most serious over a period of time.

TABLE 1

Mark	^{226}Ra(mg/g)	^{90}Sr(mc/g)
10	0·09	0·17
8	0·05	0·17
6	0·038	—
4	0·020	—
L 130	0·020	1·0
L 200	0·020	1·5
L 40	0·010	0·20
L 30	0·006	0·15

The data given by the manufacturer were checked by means of radiophysical analysis (Fig. 1).

EXPERIMENTAL METHODS

(1) *External radiation*

Since none of the methods for personal monitoring of external exposure had been introduced in the workplaces examined we made use of measurements with a standard gamma-ray ionization chamber (1). In order to eliminate the contribution of bremsstrahlung from ^{90}Y the walls of the chamber were modified and the change was allowed for in calibration. Detailed knowledge of the operation and the variable time spent by workers at certain places was used for interpreting the readings. Even though the integration method of personal dosimetry cannot be entirely substituted in this fashion, results in agreement with health physical calculations (shielding of manipulation boxes and of containers, considering time and distance factors) proved that the gamma-ray dose intensities were below the maximum permissible level. Only at places where quality control of finished dials was carried out did the beta-ray doses reach 5 rad/hr within the working distance. The surface beta doses were checked by means of measurements with an extrapolation chamber as shown in Fig. 2 (2). During assembly and testing an evaluation was made of the importance of external irradiation of the workers from surfaces of gadgets coated with radioluminous substances; the time during which articles were in worker's hands, and the piling up of finished products on the work-table were taken into consideration. Attention was also paid to the possible exposure of personnel not engaged in the work with radioactive substances.

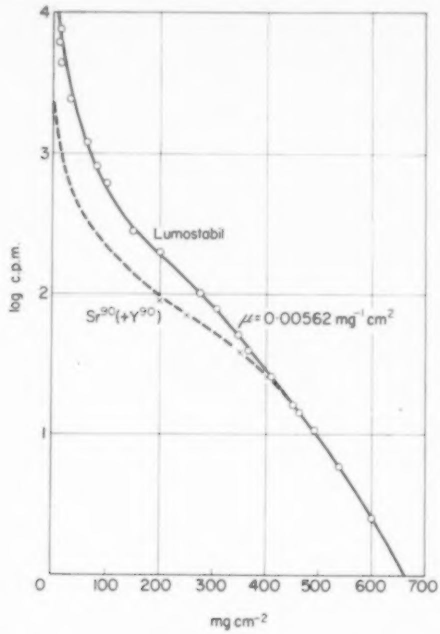

FIG. 1. Absorption curve for Lumostabil No. 130 in comparison with absorption curve for ^{90}Sr ($+ {}^{90}Y$).

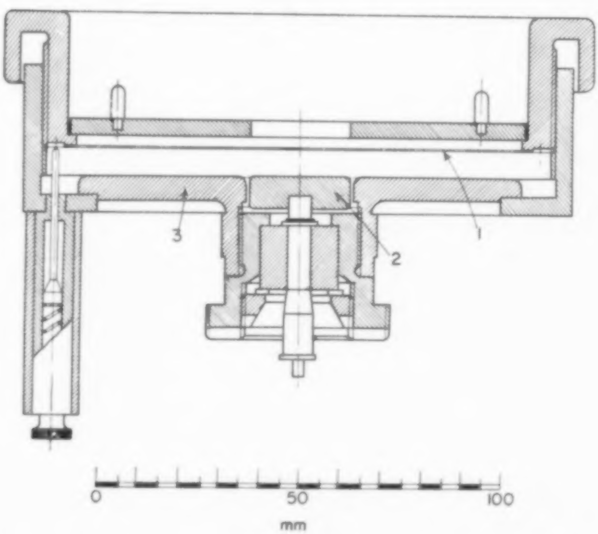

FIG. 2. Extrapolation chamber. 1—high voltage electrode (Terylene coated with Al–1 mg/cm^2); 2—collector (brass); 3—guard ring (brass).

Activities of articles were checked by measurements in a universal re-entrant chamber [Fig. 3 (3)]. These investigations showed doses below the maximum permissible level (0·3 rem/week) assigned to workers dealing with ionizing radiation, but several times

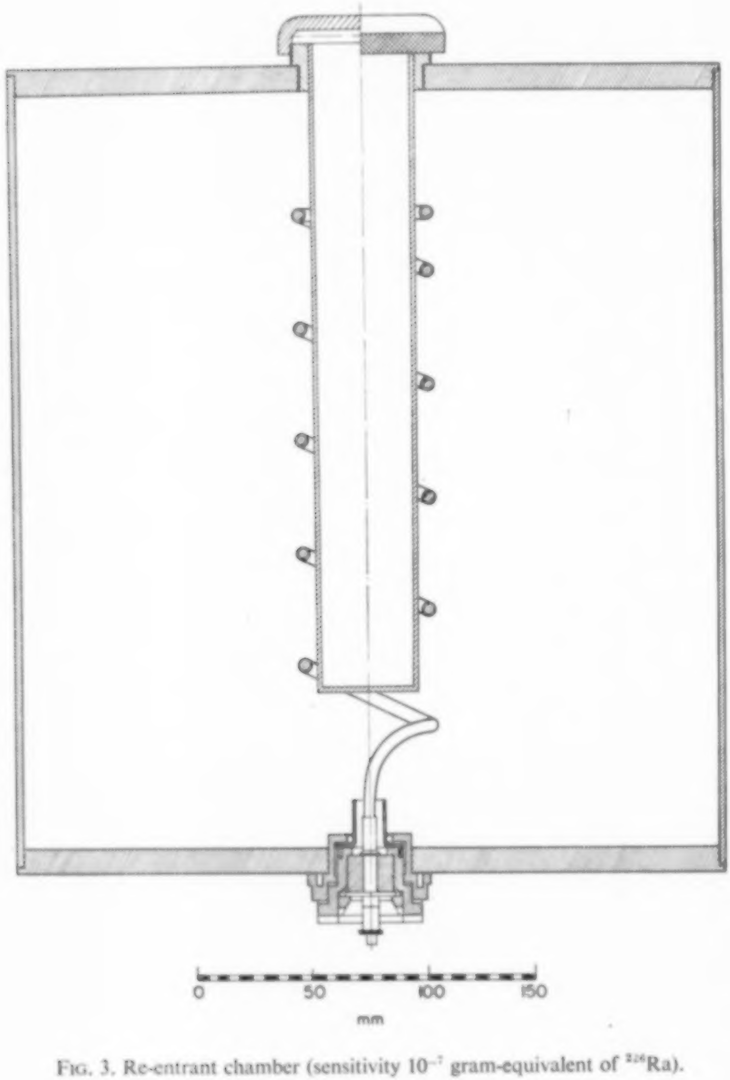

FIG. 3. Re-entrant chamber (sensitivity 10^{-7} gram-equivalent of ^{226}Ra).

higher than is permissible for persons not working with ionizing radiation. For this reason it is necessary that numerous groups of workers engaged in fitting up, testing and repairing of products in question be included as well as the small group of persons working with radioactive materials.

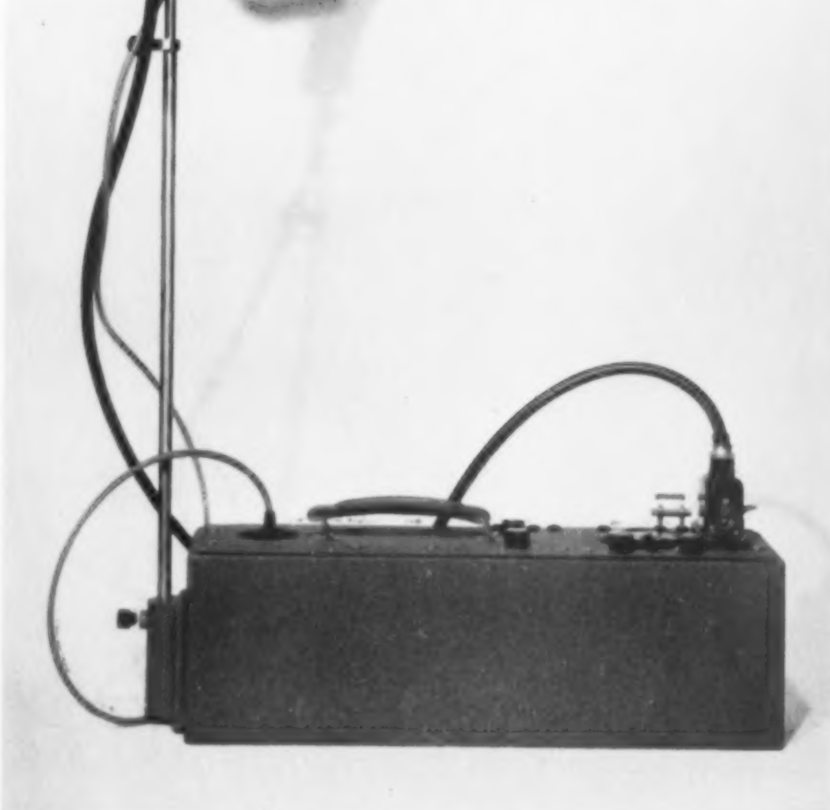

FIG. 4. Electroprecipitator with linear movement of the field (6 l/min, 7 Kv, eff. ~100 per cent).

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(2) *Contamination*

In all workshops where radioluminous substances were handled inadmissible surface contamination was found which was due to the following causes:

(*a*) carelessness during application,
(*b*) harsh manipulation of coated articles,
(*c*) improper cleaning procedure.

While the first type of contamination can easily be localized the second and the third cause spreading of contamination to distant places, and originate radioactive aerosols. Because of the quickly changing activity, we employed a method consisting of taking off the contaminant with adhesive strips (200 cm^2) of Sellotape. In this way the efficiency of decontamination equalled nearly 100 per cent (smooth, hard surfaces). The stripped pieces of Sellotape were shaped into the form of cubes, placed in glass ampullae and sealed. After equilibrium was reached these samples were measured in a re-entrant chamber for gamma radiation. The average activity found was 10^{-3} μc Ra/cm^2 and $5 \cdot 10^{-2}$ μc ^{90}Sr/cm^2. When wet methods were employed for cleaning, their efficiency did not attain more than a few per cent. In addition, this cleaning resulted in the contamination of surfaces originally clean or only slightly contaminated.

In the cases described, contamination by radioactive aerosols cannot be separated from the spontaneous spread of activity (through walking, cleaning, etc.) since the origin of the former is closely connected with the latter. In order to determine the concentration of radioactive aerosols in the atmosphere, an electroprecipitator [Fig. 4 (4)] was used. Since the vigilance of supervisors was stimulated by previous visits of health physicists the concentrations of aerosols did not correspond to the degree of contamination found before. Nevertheless, concentrations up to 10^{-9} μc Ra/cm^3 were found on certain days. For this reason strips of Sellotape were inconspicuously placed at different places inaccessible to cleaning, and left to be exposed to the fall-out during a period of 1 week. It is obvious that this method is not able to give a real picture of the distribution of micron and submicron particles which hardly sediment at all under the given circumstances. In spite of this fact, however, the method provides more adequate data than those obtained by sampling for a short time. The evaluation of sedimented aerosols was carried out in the same way as in the case of surface contamination. Values found corresponded to the activity taken off contaminated surfaces. The surface and spatial contamination of the work area resulted in an inadmissible surface contamination as well as internal contamination of workers. For quantitative estimation of the degree of residual contamination (after the current decontamination at the end of the workday) a new method of measuring *in vivo* (5) was used. Our first objective when elaborating this method was to present as simple an arrangement as possible so that it could be used even in modestly equipped laboratories. The principle involved was the use of two scintillation NaI (Tl) crystals in an optimum geometry (Fig. 5). By means of this method a contamination of persons working with radioluminous substances as high as 10^{-6} c Ra was observed. In cases where decontamination of persons was successful or in those where persons did not show any surface contamination at all (checked locally with a probe Tiss) the incorporated activity was measured in the way shown in Fig. 6. In most cases values thus obtained did not exceed the maximum permissible level. In some cases, however,

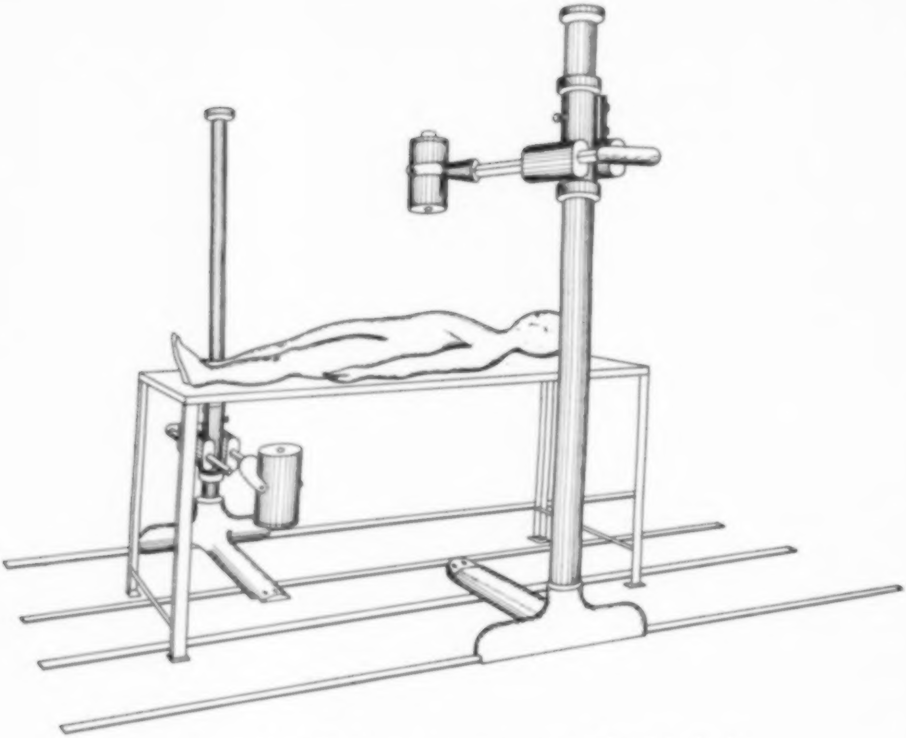

FIG. 5. Use of scintillation counters to measure radioactivity *in vivo*.

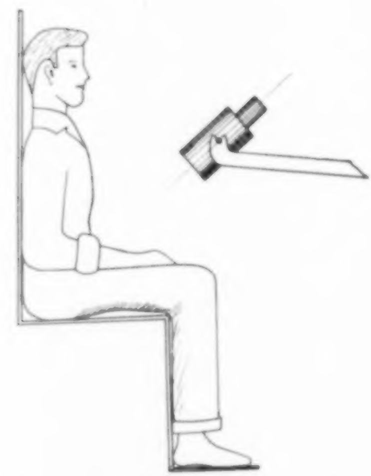

FIG. 6. Measurement of incorporated activity when surface contamination was absent.

(persons working more than 2 years) the incorporated activities were found to correspond to 10^{-6} c ^{226}Ra—for the whole body. The activity of Sr^{90} found in a daily portion of urine reached up to 10^{-4} μc (J. MÜLLER, personal communication).

Decontamination of persons was carried out to distinguish between the internal contamination and the surface contamination on the one hand, and to estimate the effectiveness of decontamination normally done by workers at the end of every workday, on the other hand. As to detergents, white soap of a good quality and medicinal soap were used for decontamination of the body; a 1 per cent solution of Chelaton 3 (EDTA) was used for hands and hair. In addition, suspension of tricalcium phosphate was applied for decontamination of hands. By means of these methods the decontamination of the whole body reached 70 per cent on the average, and Chelaton 3 proved to be the most efficient. For decontamination of work clothes a 5 per cent solution of Chelaton 3 (pH 5·5; 80°C) was used with the average efficiency of 95 per cent. The efficiency of decontamination was determined by local measurements with a beta probe and by whole body gamma measurements.

(3) *Spread of activity*

The contamination of surfaces in the workplaces in question, and the traffic of articles during erection and testing resulted in surface contamination of assembly shops and testing rooms. This effect was supported by the fact that persons employed in erection had not been instructed sufficiently as to the potential risk (rubbing, exposure due to piled up articles, etc.), the risk being considered as absurd by the supervisors. Unfortunately, contamination entered even wardrobes and drawers which often contained luncheon parcels. In these cases, however, the contamination was not so disturbing as the contamination of the actual work areas. Similarly to other cases, even there the contamination was measured with the beta probe of the Soviet instrument Tiss. The contamination of the actual work areas had a rather alarming consequence, namely the contamination of workers' homes; fortunately this was not very serious.

CONCLUSION

The main objective of this paper has been to show that, even with the latest preventive techniques, which at first sight seem to be quite sufficient (surfaces of a good quality, manipulation boxes, ventilation, etc.), the mentality of workers handling radioactive material plays an important role since unfavourable morale may be detrimental to a wider neighbourhood. In connection with this fact the importance of instructing workers as to the existing dangers as well as how to minimize or completely remove them is quite evident.

Our Health Physics Division has, therefore, been carrying out a detailed examination of all workplaces dealing with radioactive materials, the degree of importance being as follows: workplaces with radioluminous paints, medical laboratories, industrial workplaces, and the remaining establishments. An immediate removal of defects, increase of the professional discipline of workers dealing with radioactive substances, and the obtaining of precise knowledge of types and degrees of various dangers has been the result. As in the case of radioluminous paints new recommendations for protection against ionizing radiation are to be elaborated for individual branches of this work.

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APPARATUS FOR STRIPPING AND MEASURING RADIOACTIVE SURFACE CONTAMINANTS

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ANY action taken in a radioactive area may cause or spread contamination. This radioactive contamination is objectionable, and its harmful effects to the health of people working in the affected area as well as to the technical operations are well known already. The control of contamination is a complex subject, decontamination being an essential part of it. However, decontamination, especially in the case of surface contamination by radioactive aerosols or residual small crystals of radioactive materials, is very difficult.

The contamination of working surfaces by complex gamma-beta emitters cannot easily be detected on the spot, as the results of the local measurement are affected in an undefined way by the surroundings. It is therefore of great advantage to take off the contaminating material and to measure its activity at another place.

The apparatus further described enables the control and removal of surface contamination with high efficiency.

The apparatus is based on the method of adhesive decontamination (BORN, 1958). A highly adhesive tape, such as Sellotape, is uncoiled from drum No. 1 and runs over rubber-coated drums 2 and 3 (Fig. 1). By pressing the apparatus in the direction of arrow A, the adhesive tape is made to fit closely to the surface and the whole

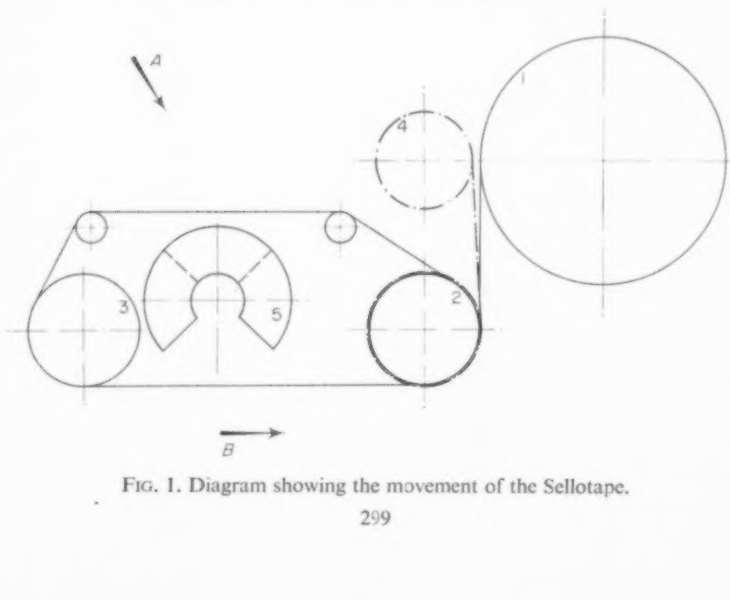

FIG. 1. Diagram showing the movement of the Sellotape.

instrument shifts in the direction of arrow B. This movement results in the continuous shifting of the tape and its rewinding on drum No. 2. The apparatus is provided with a collimated G.M. tube for measuring the contaminated surface on the one hand, and the stripped contaminant on the other hand, as the lead case (5) is turned through 180°. Detection can be carried out either with the aid of earphones or with one of the well-known integrating circuits. More precise evaluation can be obtained in the laboratory (counting room) if the contaminant is automatically covered up by a paper tape uncoiling from drum No. 4 so that the coil can be unwound. The apparatus described is shown in Figs. 2–5.

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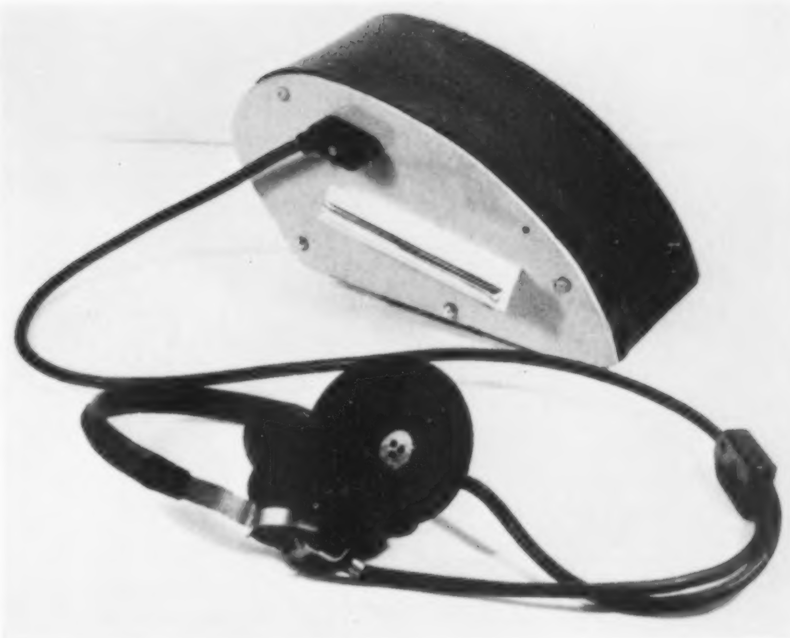

FIG. 2. The decontaminator.

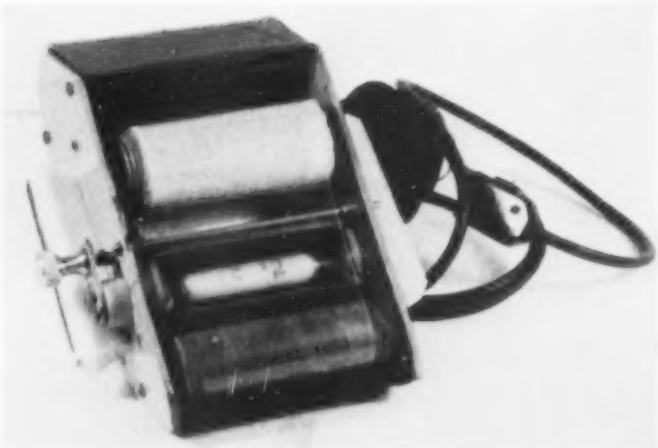

FIG. 3. The view on the bottom of the device.

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FIG. 4. The folding cover raised for exchanging the tapes.

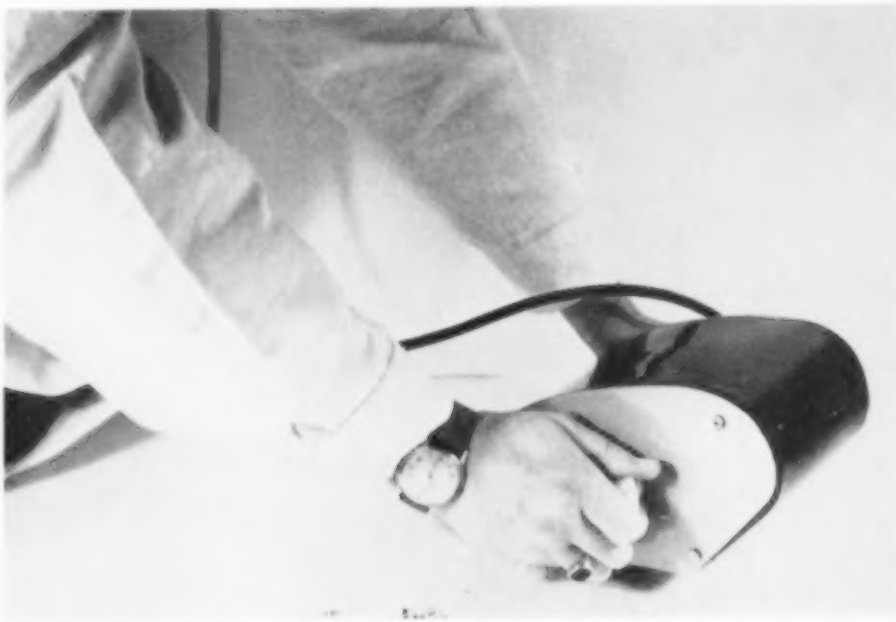

FIG. 5. Manipulating the decontaminator.

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COLLECTION EFFICIENCIES OF A CASCADE FILTRATION DEVICE EMPLOYING WIRE GAUZES*

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Abstract

Tests to evaluate the performance of a cascade filtration air sampler are described. Gross efficiencies for each filtration stage are given for the collection of uranium dioxide dust and sodium chloride aerosols at various flow rates. Empirical relationships for collection efficiency as a function of the inertial parameter of a particle are given.

I. INTRODUCTION

THIS report summarizes the work done to evaluate the performance characteristics of a cascade filtration device. The work comprised efforts to determine (*a*) the gross collection efficiencies of each of the first two stages when used at various flow rates to sample aerosols of uranium dioxide and sodium chloride, and (*b*) the collection efficiency, as a function of particle size, for each of the first two stages when used in sampling an aerosol at 15 l/min.

II. DESCRIPTION OF THE DEVICE

The device is essentially a lucite tube arranged to hold three filtering media in series. The first filtration stage (Fig. 1) is a 325-mesh metal screen. Its openings

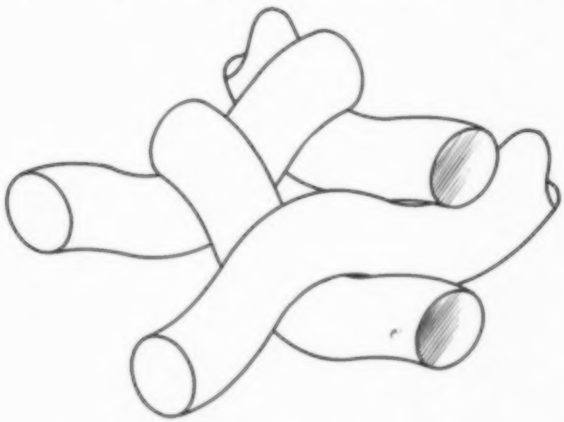

FIG. 1. Construction detail of stage I screen.

* This paper is based on work performed under contract with the United States Atomic Energy Commission at the University of Rochester Atomic Energy Project, Rochester, N.Y. The screen array described herein is typical of an instrument designed by H. L. Rarrick for Sandia Corporation, Albuquerque, N. M., who used a number of them in field experiments in 1957 and then requested and supported this evaluation of the basic design.

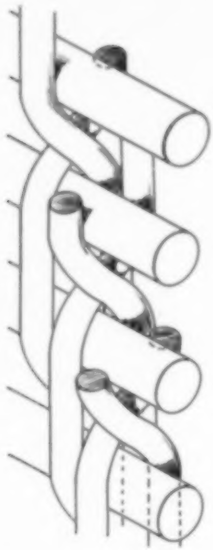

Fig. 2. Construction detail of stage II screen. (Manufactured by Aircraft Porous Media, Inc., Glen Cove, N.Y.)

are approximately square, 45 microns on a side, and the wires are approximately 34 microns in diameter. Of its total cross-sectional area, 33 per cent is open.

The second filtration stage (Fig. 2) is a tightly woven wire gauze which is less readily characterized. For this reason, it has been considered as a "filter pad" and certain average characteristics have been calculated for it. The physical dimensions and the flow characteristics of each of these first two stages are summarized in Tables 1 and 2 respectively.

Table 1. Physical dimensions of stages I and II

	Wire diameter (microns)	Thickness* ($x \cdot 10^{-4}$ cm)	Area (cm^2)	Packing density†
Stage I	34	81	6·44	0·29
Stage II	~30	145	7·95	0·59

* Measured by micrometer.
† Packing density = fiber volume/total volume.

In calculating the flow characteristics, the average linear velocity through the filter was obtained from the formula (Davies, 1952)

$$v = 16{\cdot}67\ Q/A(1-c)$$

where Q is the flow rate in l/min, A is the cross-sectional area of the filter and c is the packing density. Reynolds numbers calculated for the two stages at these velocities

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TABLE 2. FLOW VELOCITIES THROUGH STAGES I AND II

	Stage I		Stage II	
Volume flow rate, Q (l/min)	v* (cm/s) v*	v_0† (cm/s) v_0†	v (cm/s) v	v_0 (cm/s) v_0
5	18·2	12·9	25·5	10·5
15	54·8	38·8	76·6	31·5
25	91·3	64·6	127·6	52·5

* v = average linear velocity.
† v_0 = upstream linear velocity.

are between 0·4 and 3·0. In the case of an isolated cylinder, then, streamline, or near streamline, flow around the wire would be expected. This may not be true for a filter, however (DAVIES, 1952).

The third stage is a Millipore filter, either type HA or type AA. The distance of separation between stages is 1 in.

III. DETERMINATION OF THE GROSS COLLECTION EFFICIENCIES

A. Experimental method

The gross collection efficiencies of the first two stages were determined at three different flow rates using UO_2 and NaCl aerosols. The mass distributions are shown in Table 3. The distribution for the UO_2 aerosol was obtained from samples collected on millipore filter and treated for examination in the electron microscope. The NaCl aerosols were sampled for particle size distribution by means of both a thermal precipitator and an electrostatic precipitator. For UO_2, the term "diameter" refers to the length of the projection of the particle on a fixed reference line. For NaCl, the term refers to the length of the side of the cubical particle.

TABLE 3. MASS DISTRIBUTIONS OF THE TEST AEROSOLS

Aerosol	Mass median diameter (microns)	Geometric standard deviation
UO_2	2·2	2·3
1% NaCl*	0·4	2·2
10% NaCl*	0·9	2·4

* The concentration of the solution from which the aerosol was aspirated.

The NaCl aerosols were obtained by aspiration of solutions having weight concentrations of salt of 1 per cent and 10 per cent. The aerosol generator used was of the type described by LAUTERBACH *et al.* (1956). The moist air containing the aspirated droplets was mixed immediately with dry, filtered air in a chamber of 20 l. capacity.

The relative humidity in this chamber was approximately 33 per cent, at which value the evaporation of the droplets to form salt crystals should have been complete before the aerosol reached the sampler.

The samples were drawn directly from the mixing chamber. The screen under test was used in both stages of the sampler, as a means of estimating the existence of "cut-off" values. After collection of a sample, each of the screens and the millipore filter of the third stage were washed with distilled water to recover the salt. The washing was brought up to 50 ml with additional distilled water. This was divided into two 25 ml samples, each of which was analysed for chloride content by the method of Smit as modified by Berke and DiPasqua (1957). At the end of a series of samples, the device was washed out with distilled water and the washings analysed for chloride to determine the amount of salt lost to the sampler itself. It was found that less than 2 per cent of the salt entering the sampler was deposited on surfaces other than those of the three collection stages.

The UO_2 aerosols were produced by means of a Wright feed generator. The UO_2, mixed with diluting air, was introduced into a test chamber of approximately 2 m^3 capacity, similar to that described in detail by Laskin *et al.* (1948). An aerosol concentration of approximately 45 mg/m^3 was maintained in the chamber.

Samples were collected at three flow rates. Again the screen under test was used in both stages. The UO_2 collected was analysed by placing the screen or millipore filter in a scintillation type alpha counter to determine the radioactivity on the sample. This has been shown to be an adequate method in the case of the millipore filters (Mercer, 1954); however, it was necessary to carry out separate tests to determine the counting geometry of each of the screens. To do this, a sample was collected with the first two stages of the sampler vacant. This was followed by a sample in which only the second stage was vacant, the first stage being occupied by the screen under test. Then a second sample was collected with the first two stages again vacant. The difference between the amount collected on the second sample and the average amount collected on the first and third samples was taken to be the actual amount collected by the screen. The screen was then counted and the ratio of the amount of UO_2 indicated by this count to the actual amount collected was taken to be the counting geometry of the screen. These values are summarized in Table 4.

Table 4. Counting geometries of stages I and II

	Number of determinations	Counting geometry	Standard deviation
Stage I	10	0·50	0·10
Stage II	10	0·32	0·04

B. Experimental results

The results of the tests in which screens of the same type were used in both stages I and II are summarized in Tables 5 and 6.

Tests were also carried out using the device in the normal fashion. The results are shown in Table 7.

IV. INTERPRETATION OF RESULTS

A. Efficiencies as functions of parameters of the particle size distributions

In order to consider both the NaCl and UO_2 aerosols in the same discussion, it is helpful to make use of the quantity

$$P = mv/3\pi\eta Rd$$

which is called the inertial parameter (DAVIES, 1956). For a particle of mass m and diameter d, moving at a velocity v towards a cylindrical collector of radius R, the inertial parameter is the ratio of the stopping distance of the particle to the radius of the collector (η is the viscosity of air).

TABLE 5. GROSS COLLECTION EFFICIENCIES OF STAGE I

Stage	Aerosol	Flow rate (l/min)	Number of tests	Efficiencies in fractions*		
				E_1	E_2	E_2'
I	1% NaCl	15	7	0·038±0·020	0·034±0·014	0·035±0·015
	1% NaCl	25	5	0·088 0·018	0·060 0·010	0·065 0·011
	10% NaCl	5	6	0·104 0·044	0·063 0·005	0·074 0·009
	10% NaCl	15	4	0·121 0·025	— —	0·106 0·017
	10% NaCl	25	7	0·151 0·011	0·093 0·028	0·109 0·039
	UO_2	5	10	0·237 0·039	0·162 0·022	0·224 0·037
	UO_2	15	10	0·239 0·048	0·145 0·022	0·187 0·022
	UO_2	25	6	0·186 0·016	0·176 0·030	0·216 0·033

*E_1 = fraction of original aerosol collected by the indicated screen when in stage I position.
E_2 = fraction of original aerosol collected by identical screen in the stage II position.
E_2' = fraction of available aerosol collected by the second stage screen.
(The second figure in each column is the standard deviation on the mean value for the number of tests shown.)

TABLE 6. GROSS COLLECTION EFFICIENCIES OF STAGE II

Stage	Aerosol	Flow rate (l/min)	Number of tests	Efficiencies in fractions*		
				E_1	E_2	E_2'
II	1% NaCl	15	6	0·405±0·039	0·109±0·017	0·177±0·020
	1% NaCl	25	8	0·398 0·114	0·121 0·027	0·180 0·033
	10% NaCl	5	6	0·491 0·111	0·092 0·012	0·216 0·025
	10% NaCl	15	6	0·780 0·099	0·033 0·005	0·228 0·016
	10% NaCl	25	6	0·796 0·037	0·056 0·010	0·275 0·049
	UO_2	5	6	0·858 0·025	0·026 0·003	0·215 0·021
	UO_2	15	7	0·867 0·020	0·087 0·030	0·613 0·110
	UO_2	25	6	0·732 0·040	0·131 0·064	0·472 0·142

*E_1 = fraction of original aerosol collected by the indicated screen when in stage I position.
E_2 = fraction of original aerosol collected by identical screen in the stage II position.
E_2' = fraction of available aerosol collected by the second stage screen.
(The second figure in each column is the standard deviation on the mean value for the number of tests shown.)

In the case of UO_2, it is assumed that the particles are spheres and $P = d^2\rho v/18\eta R$, where ρ is the density of the particle. In the case of NaCl, $m = \rho s^3$ and $P = \rho s^2 v/4{\cdot}1\pi\eta R$, if d is defined by the equation $\pi d^2 = 6s^2$. Since the variable of interest is the particle diameter, the quantity $\sqrt{P}$ is used for purposes of comparison. The values of this quantity for each stage under the various flow conditions are shown in Table 8. The average linear velocity through the screen was used in making these calculations.

TABLE 7. GROSS COLLECTION EFFICIENCIES OF THE DEVICE

Aerosol	Flow rate (l/min)	Number of tests	Fraction of total sample collected on	
			Stage I	Stage II
1% NaCl	15	3	0·054 ± 0·009	0·370 ± 0·032
1% NaCl	25	3	0·099 ± 0·007	0·425 ± 0·023
10% NaCl	5	4	0·077 ± 0·020	0·378 ± 0·114
10% NaCl	15	3	0·116 ± 0·013	0·593 ± 0·089
10% NaCl	25	3	0·153 ± 0·010	0·640 ± 0·047
UO_2	5	3	0·226 ± 0·008	0·614 ± 0·011
UO_2	15	3	0·253 ± 0·064	0·617 ± 0·056
UO_2	25	3	0·190 ± 0·030	0·538 ± 0·056

In Fig. 3, the gross collection efficiencies have been plotted as functions of $\sqrt{P_m}$ where P_m is the inertial parameter of the particle of mass median diameter. The large initial slope of the stage II filter suggests a rapidly rising curve of efficiency with respect to particle size. This is also indicated by the low values of E_2 in Tables 5 and 6.

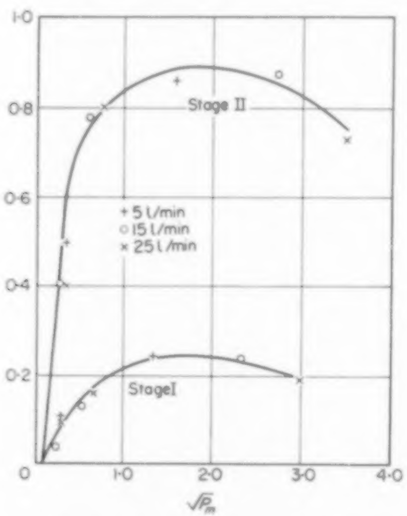

FIG. 3. Efficiencies as functions of the root inertial parameter of the particle of mass median diameter for stages I and II.

TABLE 8. ROOT INERTIAL PARAMETERS AT VARIOUS FLOW RATES

Flow rate (l/min)	$\sqrt{P}$ for UO_2*		$\sqrt{P}$ for NaCl*	
	Stage I	Stage II	Stage I	Stage II
5	0·60 *d*	0·71 *d*	0·32 *s*	0·37 *s*
15	1·04 *d*	1·23 *d*	0·55 *s*	0·65 *s*
25	1·35 *d*	1·59 *d*	0·71 *s*	0·83 *s*

* *s* and *d* are in microns.

The wide range of median diameters over which the gross efficiency is relatively constant for each stage represent a serious obstacle to making use of the device as a means of determining the mass distribution parameters of an aerosol.

B. Estimated efficiencies as functions of particle size for stage I

It was found that when the gross efficiencies in terms of the actual collecting (i.e wire) surface at 15 l/min were plotted against the logarithms of $\sqrt{P_m}$ a straight line was obtained (Fig. 4). This suggested the possibility of a relationship

$$E = a + b \ln \sqrt{P}$$

for the range of *P*-values encountered. By applying this to the "log-normal" distribution, it was possible to derive equations from which *a* and *b* could be determined

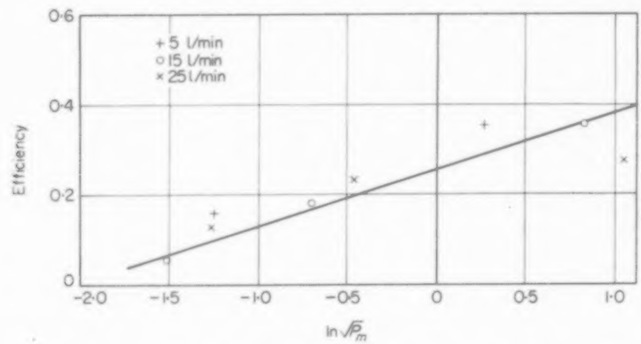

FIG. 4. Efficiencies as functions of the root inertial parameters of the particles of mass median diameter for Stage I. (The efficiency is in terms of the actual collecting surface; the indicated efficiency = 1·5 x observed efficiency.)

TABLE 9. CONSTANTS OF EFFICIENCY EQUATIONS FOR STAGE I

Flow rate (l/min)	*a*	*b*
5	0·32	0·14
15	0·26	0·12
25	0·28	0·12

by making use of the observed gross efficiencies (Appendix 1). The results for the three flow rates are summarized in Table 9.

From these equations the efficiencies for both aerosols have been calculated (Figs. 5 and 6). The efficiencies shown in the curves are in terms of the area of the actual collecting surface; when applied to the whole of stage I, they must be diminished by the factor 0·67.

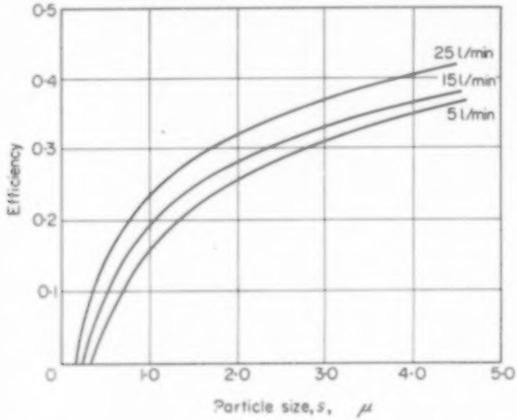

FIG. 5. Estimated collection efficiencies for stage I as functions of particle size for NaCl. (The efficiency indicated refers to the actual collecting surface.)

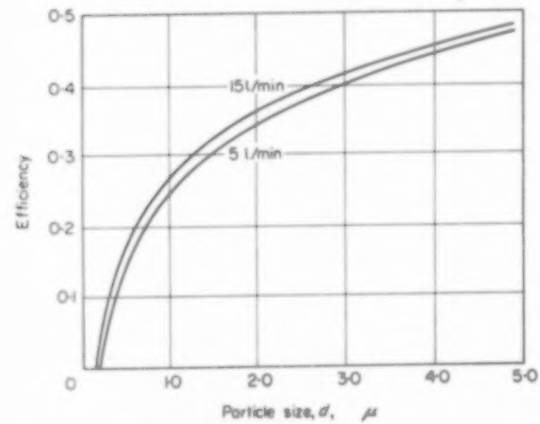

FIG. 6. Estimated collection efficiencies for stage I as functions of particle size for UO_2. (The efficiency indicated refers to the actual collecting surface.)

Using these curves, values for E_1 and E_2 have been calculated for the various aerosols (Table 10). The values for E_1 are necessarily similar to the observed values shown in Table 5, since most of them were used in determining the constants a and b. Comparisons of the calculated values of E_2 with those in Table 5, however, represent

independent checks on the validity of the curves. While the calculated values generally run higher than the observed values, the agreement is reasonably good considering the differences among the various aeosols used.

TABLE 10. CALCULATED VALUES OF E_1 AND E_2 FOR STAGE I

Flow rate (l/min)	Aerosol	E_1	E_2
5	10% NaCl	0·103	0·086
	UO_2	0·243	0·179
15	1% NaCl	0·063	0·056
	10% NaCl	0·124	0·103
	UO_2	0·249	0·186
25	1% NaCl	0·087	0·076
	10% NaCl	0·151	0·109

It is probable that the curves should pass through an optimum efficiency in the neighbourhood of $\sqrt{P} = 2{\cdot}0$. Such a modification would be necessary to explain the results on UO_2 at the higher flow rates. However, the present tests were chiefly concerned with the efficiencies at 15 l/min, at which flow rate the curves appear to be adequate as they are.

C. Estimated efficiencies as functions of particle size for stage II

The steep initial slope of the curve of Fig. 3 suggested the possibility that the efficiencies of the stage II screen could be represented by three sets of equations:

$$\begin{aligned} E &= 0, & \sqrt{P} &< \sqrt{P_1} \\ E &= (\sqrt{P}-\sqrt{P_1})/(\sqrt{P_2}-\sqrt{P_1}), & \sqrt{P_1} &< \sqrt{P} < \sqrt{P_2} \\ E &= 1, & \sqrt{P} &> \sqrt{P_2} \end{aligned}$$

In these equations, $\sqrt{P_1}$ = the root inertial parameter below which collection ceases and $\sqrt{P_2}$ = the root inertial parameter above which collection is complete. Between $\sqrt{P_1}$ and $\sqrt{P_2}$ the efficiency is assumed to be a linear function of $\sqrt{P}$.

These equations have been applied to the "log-normal" distribution to obtain expressions for the overall collection efficiency (Appendix 2). Using the observed efficiency for the 1% NaCl aerosol at 15 l/min, values of $\sqrt{P_1}$ and $\sqrt{P_2}$, determined by trial-and-error methods, were found to be 0·065 and 0·65 respectively. Applying these values to the 10% NaCl yields an overall collection efficiency of 0·78 when that aerosol is sampled at 15 l/min, almost precisely the observed value. When applied to the UO_2 aerosol, however, the results are about 10 per cent high.

The gross efficiency data indicate that the efficiency does not actually reach 1·0 in the range of sizes studied. There is also evidence that at larger values of $\sqrt{P}$ the efficiency decreases. These factors have been taken into consideration in modifying the curve corresponding to the efficiency equations above to yield the curve of efficiency as a function of $\sqrt{P}$ shown in Fig. 7.

In the same figure, the curves for efficiency as a function of particle size are shown for NaCl and UO_2. These curves have been used to estimate E_1 and E_2 for each aerosol at 15 l/min, with the results shown in Table 11.

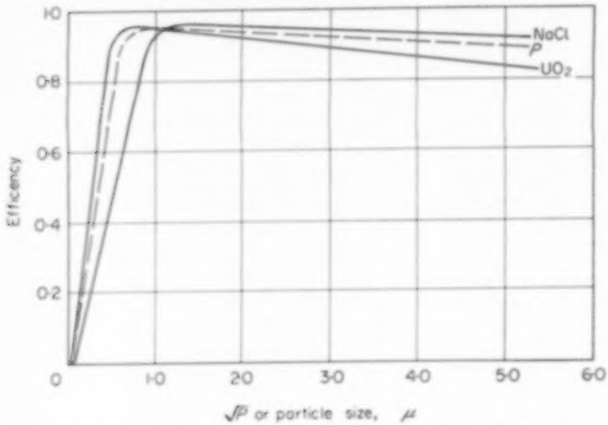

FIG. 7. Estimated collection efficiencies for stage II as functions of $\sqrt{P}$ or of particle size.

TABLE 11. CALCULATED VALUES OF E_1 AND E_2 FOR STAGE II AT 15 l/min

Aerosol	E_1	E_2
1% NaCl	0·41	0·14
10% NaCl	0·74	0·13
UO_2	0·88	0·10

While the efficiency curve for stage II is entirely empirical, a comparison of these calculated values of E_1 and E_2 with those shown in Table 6 indicates that it is reasonably accurate over the range of P-values encountered. At large particle diameters, of course, the screens actually become sieves.

D. Discussion

The loss in efficiency at higher flow rates, at least for the UO_2, may be due to shattering of aggregates, re-entrainment of particles already collected, rebounding of a particle after colliding with a wire, or a combination of these effects. The values of E_2' for UO_2 in Table 6 suggest a rebound effect.

For convenience, the curves of efficiency as a function of $\sqrt{P}$ at 15 l/min have been plotted together in Fig. 8. Possibly the stage II screen could serve as one of the stages of a particle separation device. However, at least three stages, each having an efficiency curve similar in shape to that of stage II but displaced with respect to $\sqrt{P}$, are necessary to permit an estimate of the mass distribution of an aerosol to be made from samples collected with such a device. The stage I screen would be suitable only if the mass distribution of the aerosol included a large fraction above the size for which the screen becomes a sieve.

V. SUMMARY AND CONCLUSIONS

The gross efficiencies of two stages of a cascade filtration air sampler have been determined at three different flow rates for aerosols of UO_2 and NaCl.

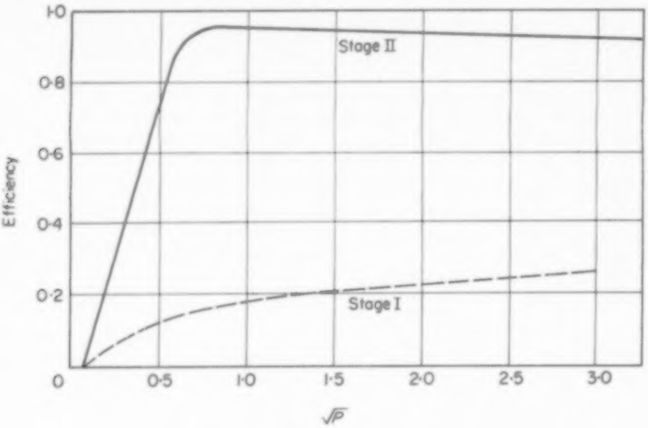

FIG. 8. Efficiency as a function of $\sqrt{P}$ at 15 l/min for stages I and II.

Estimates of the efficiencies of the two stages as functions of particle size have been made.

It is concluded that in the range of particle sizes studied this device does not provide sufficient data to make it possible to estimate the mass distribution of the aerosol sampled.

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APPENDIX 1

Estimated Efficiency Equations for Stage I

Assume that the efficiency of collection for the actual wire surface is given by the equations

$$E = 0, \qquad \sqrt{P} < \sqrt{P_1}$$
$$E = a + b\ln\sqrt{P}, \quad \sqrt{P} > \sqrt{P_1}$$

where the $\sqrt{P_1} = -a/b$ is the inertial parameter below which collection ceases.

Since the aerosols are "log-normally" distributed, the mass distribution of the incoming aerosol is

$$\mathrm{d(m)} = (M/\ln\sigma\sqrt{2\pi})\,[\exp-(\ln d - \ln d_m)^2/2\ln^2\sigma]\,\mathrm{d}(\ln d)$$

where M is the total mass of aerosol, d_m is the mass median diameter and σ is the geometric standard deviation. For a given set of sampling conditions, $d = k\sqrt{P}$ and the amount collected by the filter is

$$\Delta \mathrm{m} = \int E\mathrm{d(m)} = \frac{fM}{\sqrt{2\pi}\ln\sigma}\int_{\ln\sqrt{P_1}}^{\infty}(a + b\ln\sqrt{P})\,[\exp-(\ln\sqrt{P} - \ln\sqrt{P_m})^2/2\ln^2\sigma]\,\mathrm{d}(\ln\sqrt{P})$$

where f is the fraction of the incoming aerosol that is subject to filtration.

This yields for the gross efficiency of the collecting surface

$$E = \Delta\mathrm{m}/M = \mathrm{f}\,[(a + b\ln\sqrt{P_m})\int_{z_1}^{\infty}(1/\sqrt{2\pi})\exp-z^2/2\,\mathrm{d}z + (b\ln\sigma/\sqrt{2\pi})\exp-z_1^2/2]$$

where $$z_1 = (\ln\sqrt{P_1} - \ln\sqrt{P_m})\ln\sigma.$$

For a given flow rate, this equation can be solved by assuming various values for $\ln\sqrt{P_1}$, setting the right-hand term, with appropriate substitutions for $\ln\sigma$ and $\ln\sqrt{P_m}$, equal in turn to two observed values of E and solving for a and b. The correct values of a and b are those for which $-a/b$ is found to be equal to the assumed value of $\ln\sqrt{P_1}$.

APPENDIX 2

Determination of Unknown Constants in Assumed Efficiency Equations for Stage II

The following equations are assumed:

$$
\begin{aligned}
&E = 0, && \sqrt{P} < \sqrt{P_1} \\
&E = (\sqrt{P}-\sqrt{P_1})/(\sqrt{P_2}-\sqrt{P_1}) = (d-d_1)/(d_2-d_1), && \sqrt{P_1} < \sqrt{P} < \sqrt{P_2} \\
&E = 1, && \sqrt{P} > \sqrt{P_1}
\end{aligned}
$$

Applying these values to the "log-normal" mass distribution (see Appendix 1), one obtains for the gross efficiency

$$
E = (1/\sqrt{2\pi}\ \ln\sigma) \int_{\ln d_1}^{\ln d_2} (d-d_1)/(d_2-d_1)\,[\exp-(\ln d - \ln d_m)^2/2\ln^2\sigma] d(\ln d)
$$

$$
+ (1/\sqrt{2\pi}) \int_{\ln d_1}^{\infty} \exp-(\ln d-\ln d_m)^2/2\ln^2\sigma d(\ln d)
$$

$$
= [(d_m \exp(1/2\ln^2\sigma)]/(d_2-d_1) \int_{z_1}^{z_2} (1/\sqrt{2\pi}) \exp-z^2/2\ dz
$$

$$
- d_1/(d_2-d_1) \int_{y_1}^{y_2} (1/\sqrt{2\pi}) \exp-y^2/2\ dy + \int_{y_2}^{\infty} (1/\sqrt{2\pi}) \exp-y^2/2\ dy.
$$

where

$$
\begin{aligned}
z_1 &= (\ln d_1 - \ln d_m - \ln^2\sigma)/\ln\sigma \\
z_2 &= (\ln d_2 - \ln d_m - \ln^2\sigma)/\ln\sigma \\
y_1 &= z_1 + \ln\sigma \\
y_2 &= z_2 + \ln\sigma
\end{aligned}
$$

By trial and error, it is found that $d_2 = 1{\cdot}0$ and $d_1 = 0{\cdot}1$ yield a value of $E = 0{\cdot}39$ for the 1% NaCl aerosol at 15 l/min (observed value = 0·40). When these same values are used with the 10% NaCl a value of $E = 0{\cdot}78$ is obtained (observed value = 0·78).

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EXPERIMENTS WITH THE HEXHLET DUST SAMPLER IN BRITISH COAL MINES

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INTRODUCTION

THE bulk of the samples of airborne dust taken in connexion with the National Coal Board's Pneumoconiosis Field Research (FAY, 1957) have been collected with the standard Mark 3 Thermal Precipitator, and the results have been expressed in units of particles per cm^3 of air. Normally, the concentrations are calculated in terms of the 1–5 micron (μ) dust and a visual estimation is made on all the T.P. slides to assess the proportion of coal particles to mineral particles in that size range.

It is, however, desirable to extend the sampling programme with the object of collecting sufficient "respirable" dust for systematic compositional analysis, and for this purpose field trials have been carried out with the Hexhlet dust sampler (WRIGHT, 1954). This instrument, weighing about 14 lb, consists of a soxhlet-thimble sampler driven by compressed air and fitted with a horizontal elutriator with a theoretical "cut-off" of 50 per cent at 5 μ diameter for unit density particles. The sample thus consists of two fractions, the "respirable" (i.e. essentially below 5 μ) dust in the soxhlet thimble and the heavier (above 5 μ) fraction of the airborne dust in the elutriator. The sampling rate of the Hexhlet is 100 l/min, controlled by a critical orifice.

Four of these instruments have been used at collieries in England, Scotland and Wales to collect samples for investigation and analysis. Parallel samples were taken with the Long-running Thermal Precipitator (HAMILTON, 1956) to measure the corresponding 1–5μ dust concentrations.

OBJECTS OF THE EXPERIMENTS

The trials were designed to obtain information under the following headings:

(i) To examine the composition of the dusts arising from selected operations at different collieries, and to compare the composition of the respirable fraction of each dust with that of the heavier, elutriated fraction.

(ii) To investigate the variation in composition of the respirable dust on the coalface with time by repeating experiments after an interval of days or weeks.

(iii) To investigate the accuracy of the present routine Pneumoconiosis Field Research method of estimating the proportion of non-coal particles in the 1–5μ size range by visual discrimination on the T.P. slides.

(iv) To investigate the relationship between the mass concentration of respirable dust and the corresponding particle number count in coalface samples.

RESULTS

In the first series of trials at collieries in four different Divisions of the National Coal Board samples were collected at the return end of the coalface on different shifts, and in hard headings. Details of these samples are given in Table 1 and the corresponding analytical results in Table 2.

A second series of experiments was conducted at four different collieries, where samples were taken on the coalface on two different shifts, and each experiment was repeated after an interval of some days or weeks. The description and details of these samples are given in Tables 3 and 4.

Composition of the dusts

In the first series of experiments the results (Table 2) show wide variations in composition (ash and quartz content) between different samples, but a number of general trends are evident.

First, many of the samples show a marked difference in composition between the fraction collected in the thimble and that retained in the elutriator. In general, the elutriator fraction has higher ash and quartz contents than the corresponding thimble dust, and this tendency is repeated in the second series of experiments (Table 4).

Secondly, there is a tendency for the coalface samples of thimble dust collected on the coalgetting shift to have lower ash and quartz contents than those taken on the other shifts, but at some collieries this effect is not very marked and there are bigger differences between the two fractions of the same dust than between corresponding fractions of the dusts collected on different shifts on the same coalface.

Thirdly, the heading samples have, on the whole, higher ash and quartz contents than the coalface samples.

Variation in composition of dust with time

In the first series of experiments three successive samples (F/H1, F/H2 and F/H3) were taken in a heading at a Yorkshire colliery and the results (Table 2) showed considerable variation in the composition of the dust collected between one sample and another over a period of about a month. In a heading this is not surprising, as the composition of the strata encountered might well be subject to rapid change, and subsequent investigation has shown that the reported results agree quite well with the analyses of the corresponding pillar samples from the parent rock through which the heading was being driven (NAGELSCHMIDT, 1958). However, it was obviously desirable to study the variation in composition of the dust with time on the coalface, and the repeat samples in the second series of experiments (Table 4) show that little or no differences, as regards the ash and quartz contents of the corresponding dust fractions, occurred at any of the collieries, either on the coalgetting or on the cutting shift.

Visual estimation of proportion of coal and mineral particles

The measured ash content (per cent weight) of the thimble dust has been included in the last column in Tables 1 and 3 for easy comparison with the estimated proportion of non-coal particles in the corresponding Long-running T.P. samples (expressed as percentage of total number of particles in the 1–5 μ range).

In the first series of experiments (Table 1) good agreement was obtained at two of

the four collieries. At the other two collieries the investigators were at the time tending to over-estimate and under-estimate the proportion of non-coal particles compared with the rest of the team. By the time the second series of experiments was in progress (Table 3) all the investigators concerned had had more experience of visual discrimination and the agreement is more consistent. Considering all the difficulties (e.g. small numbers of particles involved, comparison of mass analysis with number count, and the great effect on composition of a small proportion of relatively large particles), the standard of visual discrimination is reasonably good.

Relationship between mass and number count

The results obtained on the coalface on all shifts in both series of experiments are shown at Fig. 1, where the mass concentration of respirable dust (in terms of mg of dust collected in the thimble per m^3 of air sampled) is plotted against the number count (in terms of particles of 1μ and above per cm^3 of air in the corresponding Long-running Thermal Precipitator samples). The count of particles of 1μ and above on the Long-running Thermal Precipitator is used because this parameter gives the best correlation with 1–5 μ count on the standard Thermal Precipitator (HAMILTON, 1956), and the results are thus suitable for consideration in terms of the "approved" levels of dustiness for British coalmines (N.C.B., 1948). For all coal dust except that arising from anthracite this approved level is 850 particles/cm^3, 1–5 μ, as measured on the standard Thermal Precipitator.

In the present experiments no obvious differences emerged between one shift and another at any one colliery, and in Fig. 1 the results from all collieries are plotted. There are no systematic variations between the collieries in different localities except for a tendency for the "extreme" results from one Scottish colliery (ringed points) all to lie on one side of the regression line and those from one of the South Wales collieries (actually a colliery in the anthracite coalfield) to lie mostly on the other (boxed points). Although other causes are not ruled out (e.g. variations in the performances of one or other of the sampling instruments) it is interesting to note that these differences are, in fact, consistent with variations in the size distributions of the airborne dusts which have been revealed in a separate study of the results obtained in the course of the Pneumoconiosis Field Research sampling programme (FAY and ASHFORD, 1960).

However, ignoring these trends it is possible to derive a mean figure for the mass of thimble dust equivalent to a given particle number count. On this basis the "approved" level (850 particles/cm^3, 1–5 μ) for non-anthracite coal dust corresponds to about 21 mg/m^3 of respirable dust, with a standard deviation of 4 mg/m^3.

It is interesting to compare this result with values obtained from other sources. Thus, calculations by BEDFORD and WARNER (1943) on samples of coal dusts in South Wales produced a figure of about 12·5 mg/m^3, the differences being not unexpected when it is considered that in the present Hexhlet experiments an elutriator was employed, with a "cut-off" performance dependent upon the falling speeds of the particles, whereas in Bedford and Warner's calculated figure no account was taken of the "shape factor" of the particles counted. Another series of independent experiments with membrane filters in the East Midlands Division of the National Coal Board gave a figure of 8 mg/m^3 corresponding to the "approved" level in the Notting-

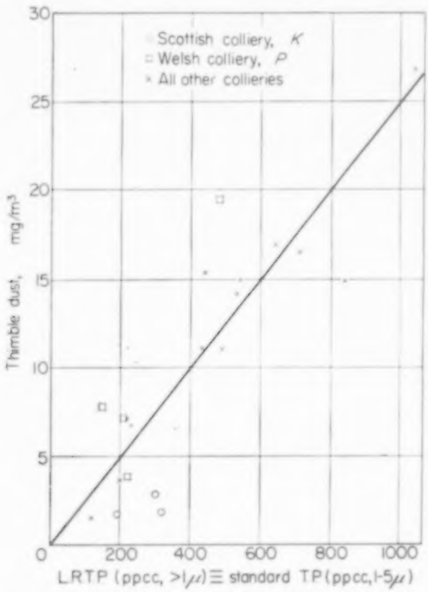

FIG. 1. Relationship between mass and number concentrations. Coalface samples (all shifts).

hamshire and North Derbyshire coalfield (POTTER and PEPPER, 1958). The authors emphasize, however, that this conclusion is based on strictly limited data and that the figure is much lower than the one they had previously obtained, using a different technique. In these latter experiments, using alignate yarn filters, the "best estimate of a conversion factor" was 34 mg/m³ corresponding to 850 particles/cm³, 1–5 μ (PEPPER, 1958).

DISCUSSION AND CONCLUSIONS

The experiments described in this report are relatively few in number but they show that the use of an elutriator to remove the heavier airborne particles is required to ensure the collection of a truly representative sample of the "respirable" fraction of the dust. The composition of samples taken in hard headings varies considerably with time, but samples on the coalface seem to remain fairly constant in composition, on a given shift, at least over relatively short periods. At first sight, therefore, the implications of these results on a systematic programme of study of environmental conditions, such as that of the Pneumoconiosis Field Research, might appear to be favourable. There are, however, several other factors which have to be taken into account.

In the first place, the only production model of the Hexhlet is driven by compressed air, and this immediately limits its application to a relatively small fraction of the coalfaces, headings and other working places in British coal mines. The tendency nowadays is for compressed air to be used less, so this drawback will be increasingly important as time goes on. Nor is it feasible to select, even at those collieries with compressed air laid on at some of the working places, a few "typical" sampling positions, in view of the variations in composition with place which have been found.

This particular problem has been tackled by the current development by the Mining Research Establishment of the National Coal Board of an electrically driven version of the Hexhlet, but the indications are that the first prototype model will weigh the best part of 200 lb, and this severely limits its application as a versatile sampling instrument.

Secondly, there is the question of time and expense. In spite of encountered delays in the course of the experiments (sometimes caused by breakdown of the instrument and sometimes by temporary non-availability of compressed air supplies) the Hexhlet did succeed in producing samples of thimble dust in sufficient quantities for analysis. In theory, on the basis of 850 particles/cm^3 (1–5 μ) being equivalent to 21 mg/m^3 of thimble dust, 1 g is collected in about 8 hr, at the specified sampling rate of 100 l/min, and this figure is in agreement with that quoted by the designer. In practice, however, travelling time, stoppages, breakdowns, etc., introduce a delay factor of at least 2, and in lower dust concentrations the time required to collect a suitable sample is, of course, correspondingly longer. For example, in a mean dust concentration of 200 particles/cm^3 (1–5 μ), 2 or 3 weeks might easily be required to obtain 1 g of dust in the thimble, and even so, if this dust has an ash content of 10 per cent, something less than 100 mg of specimen is available for analysis. Since experience in these experiments has proved that the instrument has to be attended continuously by a skilled operator, it follows the the specimen has cost something like £400/g to obtain in a form suitable for analysis.

On these grounds, it appears that the standard, compressed-air driven Hexhlet is a useful instrument for obtaining occasional, particularly important samples for research purposes, but is not suitable for routine use in an extensive and systematic programme such as the Pneumoconiosis Field Research. For the latter purposes an instrument is needed which is robust and simple to use, independent of colliery power supplies and capable of working for long periods without attention. The design of such an apparatus is now being considered jointly by the National Coal Board's Mining Research Establishment and the Safety in Mines Research Establishment of the Ministry of Power.

In the meantime, some useful but limited information about the composition of the airborne dusts at the Pneumoconiosis Field Research collieries is being obtained by the visual discrimination between coal and non-coal on the routine Thermal Precipitator samples. The experiments described show that the standard of performance of the P.F.R. investigators in this task is fairly good. An additional source of information is obtained by an analysis of samples from the coal seams and associated strata at all the P.F.R. collieries. This work is regularly being carried out by the Board's Coal Survey Organization and the Safety in Mines Research Establishment. Although the present experiments have shown that the composition of the airborne dusts varies with the size fraction, the accumulation of a knowledge of the composition of the coal and rock strata at the collieries concerned provides a useful background on which to investigate the effect of composition of dust on, for example, radiological pneumoconiosis.

Acknowledgements—My thanks are due to the investigators in the P.F.R. team who collected the samples; to Mr. A. M. Wandless and the Coal Survey Officers who analysed the samples for ash content; and to Dr. G. Nagleschmidt, of S.M.R.E., who undertook the analysis of the ashed samples for content of quartz and other minerals.

The investigations described form part of the National Coal Board's Pneumoconiosis Field Research and the results are published by permission of the Board.

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TABLE 1. DESCRIPTION OF SAMPLES (1ST SERIES)

Ref. No.	Locality of colliery	Place of sampling	Shift	Date (1956)	Concentration of "respirable" dust		Non-coal particles (1–5 μ) Visual estimate on L.R.T.P. slides (%)	Ash (% wt. in thimble dust)
					Hexhlet thimble dust (mg/m^3)	L.R.T.P. (particles/cm^3, 1 μ and above)		
K/S	Scotland	Coalface	Coalgetting	April–May	1·8	320	35	28
K/B	Scotland	Coalface	Ripping	May–June	2·8	300	60	53
K/C	Scotland	Coalface	Cutting	June–July	1·7	190	30	44
K/H	Scotland	Heading	All	August–September	0·66	110	30	31
F/F	Yorkshire	Coalface	Coalgetting	March	27	1030	20	12
F/C	Yorkshire	Coalface	Cutting	April	15	840	50	45
F/H1	Yorkshire	Heading	All	April (24–27)	3·0	420	75	68
F/H2	Yorkshire	Heading	All	May (7–11)	3·1	600	85	90
F/H3	Yorkshire	Heading	All	May (14–25)	2·3	—*	70	79
B/F	Lancashire	Coalface	Coalgetting	March	17	640	45	17
B/C	Lancashire	Coalface	Cutting	March–April	15	540	30	17
Ha/H	N. Wales	Heading	All	July–October	2·7	150	80	63
DN/F	S. Wales	Coalface	Coalgetting	March	11	490	5	7
DN/B	S. Wales	Coalface	Belt-turning	March–June	1·5	120	25	50
DN/C	S. Wales	Coalface	Cutting	June–July	3·6	200	20	42

* No sample available.

TABLE 2. ANALYSIS OF SAMPLES (1ST SERIES)

Ref. No.	Description	Thimble dust			Elutriator dust		
		Ash (% wt. of dust)	Quartz content		Ash (% wt. of dust)	Quartz content	
			(% wt. of ash)	(% wt. of dust)		(% wt. of ash)	(% wt. of dust)
K/S	Coalface—coalgetting	28	5	1·4	64	30	19
K/B	Coalface—ripping	53	5	2·6	56	24	13
K/C	Coalface—cutting	44	11	4·8	70	24	17
K/H	Heading	31	20	6·2	64	32	20
F/F	Coalface—coalgetting	12	1	0·1	12	5	0·6
F/C	Coalface—cutting	45	10	4·5	62	17	11
F/H1	Heading (1)	68	9	6·1	72	21	15
F/H2	Heading (2)	90	39	35	96	45	43
F/H3	Heading (3)	79	23	18	85	31	26
B/F	Coalface—coalgetting	17	7	1·2	32	10	3·2
B/C	Coalface—cutting	17	8	1·4	28	10	2·8
Ha/H	Heading	63	11	6·9	62	17	11
DN/F	Coalface—coalgetting	7	8	0·6	11	9	1·0
DN/B	Coalface—belt-turning	50	14	7·0	46	24	11
DN/C	Coalface—cutting	42	14	5·9	48	23	11

TABLE 3. DESCRIPTION OF SAMPLES (2ND SERIES)

Ref. No.	Locality of colliery	Place of sampling	Shift	Date	Concentration of "respirable" dust: Hexlet thimble dust (mg/m³)	Concentration of "respirable" dust: L.R.T.P. (particles/cm³, 1 μ and above)	Non-coal particles (1–5 μ) Visual estimate on L.R.T.P. slides (%)	Ash (% wt. in thimble dust)
M/H/F	Scotland	Coalface	Coalgetting	December 1957	1·0	45	67	—[a]
D/9/F/1	Yorkshire	Coalface	Coalgetting	July 1957	6·7	230	29	22
D/9/F/2	Yorkshire	Coalface	Coalgetting	August–September 1957	7·1	220	27	20
H/3/F/1	Cumberland	Coalface	Coalgetting	October 1957	11·2	430	13	12
H/3/F/2	Cumberland	Coalface	Coalgetting	February 1958	14·2	530	21	14
H/3/C/1	Cumberland	Coalface	Cutting	November 1957	15·4	440	12	10
H/3/C/2	Cumberland	Coalface	Cutting	April 1958	16·6	710	18	9[b]
P/K/F/1	S. Wales	Coalface	Coalgetting	July 1957	7·1	210	26	—[c]
P/K/F/2	S. Wales	Coalface	Coalgetting	September 1957	19·5	480	50	—
P/K/C/1	S. Wales	Coalface	Cutting	August 1957	3·8	220	63	—
P/K/C/2	S. Wales	Coalface	Cutting	October 1957	7·8	150	52	—

([a]) Compressed air ceased to be available during the course of the experiment. A duplicate sample could not therefore be collected and the sample obtained was insufficient for analysis.

([b]) The location of the repeat sample was slightly different from that of the first sample on the cutting shift, due to a change in procedure on the face.

([c]) No figures are available for comparison with the preceding column, as the first set of samples was lost in an accident. The samples from this colliery described in Table 4 are a repeat set.

TABLE 4. ANALYSIS OF SAMPLES (2ND SERIES)

Ref. No.	Description	Thimble dust			Elutriator dust		
		Ash (% wt. of dust)	Quartz content		Ash (% wt. of dust)	Quartz content	
			(% wt. of ash)	(% wt. of dust)		(% wt. of ash)	(% wt. of dust)
D/9/F/1	Coalface—coalgetting	22	9	2·0	24	8	1·9
D/9/F/2	Coalface—coalgetting	20	7	1·4	31	12	3·7
H/3/F/1	Coalface—coalgetting	12	6	0·7	22	8	1·7
H/3/F/2	Coalface—coalgetting	14	4	0·6	24	8	1·9
H/3/C/1	Coalface—cutting	10	5	0·5	16	5	0·8
H/3/C/2	Coalface—cutting	9	3	0·3	18	4	0·7
P/K/F/1X	Coalface—coalgetting	17	11	1·8	30	18	5·4
P/K/F/2X	Coalface—coalgetting	20	15	3·1	30	18	5·3
P/K/C/1X	Coalface—cutting	50	19	9·6	40	20	7·9
P/K/C/2X	Coalface—cutting	50	18	9·1	35	19	6·7

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THE DURATION OF "STATIC" (SUSTAINED) CONTRACTIONS AT DIFFERENT MUSCLE TEMPERATURES

(Abstract of a paper given at a joint meeting of the British Occupational Hygiene Society and the Ergonomics Research Society)

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THE durations of sub-maximal sustained flexor contractions of the forearm were measured on a hand-grip, strain-gauge dynamometer after the muscle temperature had been altered by immersing the forearm in water at different temperatures, from 2 to 42°C. Contractions were longest in water at 18°C, when the "reference muscle temperature", measured by thermocouples placed half-way between the skin and the centre of the arm, was about 27°C. The maximum tension that the forearm could exert remained steady at reference muscle temperatures of 27°C and above, but at lower reference muscle temperatures the maximum tension that could be exerted was reduced, e.g. to 40 per cent of the original value at a reference muscle temperature of 18°C. Large temperature gradients (of up to 15°C) existed through the muscles from the skin to the centre of the forearm in cool water, so that when the temperature is measured half-way between the skin and the centre of the arm the more superficial fibres may be 5°C (or more) lower than this reference temperature.

The evidence suggests that when the reference muscle temperature is lower than 27°C the reduction in duration of sustained contractions and the fall in maximum tension that can be exerted is due to interference with nervous or neuromuscular transmission to the more superficial (and colder) muscle fibres in the forearm; thus contractions have to be made with less than the total number of existing muscle fibres. At reference muscle temperatures higher than 27°C the fall in duration of sustained contractions is not associated with any reduction in the maximum tension that can be exerted. Blood flow measured through the forearm during and after sustained contractions suggests that with increasing temperature above reference muscle temperatureof 27°C there is an accompanying increase in the rate of metabolism which results in the faster accumulation of a limiting quantity of metabolites to cause fatigue.

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BOOK REVIEW

Badania I pomiary pylowe oraz urza dzen odpylaja cych. (Tests and measurements on dust and dust collectors.) Bull. II of the Committee on the Upper Silesian Industrial Area Air Pollution Control Commission. Edited by LUDWIK TANIEWSKY. Polish Academy of Sciences, Warsaw, 1958.

THIS volume contains five technical papers on special dust problems.

The first, by Dr. J. JUDA, has the title "Mineralogical dust analyses by means of microscopical observations". The author discusses optical resolution and classifies a number of minerals in terms of their optical properties. Refractive index, dispersion and double refraction are tabulated for 49 minerals. The minimum size of particle visible, due to birefringence, when viewed between crossed polarizers, is examined and ranges from $1\,\mu$ for siderite to $40\,\mu$ for kaolinite. Identification of minerals by the immersion method is described and it is shown that by making use of phase contrast illumination, and the dispersing properties of the medium and the particle, an improved method of analysis is available. The theory of the technique is fully described and a diagram and a nomogram are provided which cover a large number of minerals and immersion liquids. Charts explaining the colour effects are presented and there are six colour photographs. A list of 16 references is given.

Prof. W. MROZOWSKA writes on "Measurements of the efficiency of dust collection". His paper reviews gravimetric, optical and counting methods of estimating dust samples. The taking of samples with isokinetic nozzles is described and a special dust-sampling rig is illustrated. Sedimentation analysis and elutriation are discussed and a chart shows terminal velocities of spherical particles between 2 and $300\,\mu$ diameter with densities ranging from 0·5 to 12 g/cm^3.

The "Circulator" dust collector for the dry precipitation of dust is described by Dr. K. MIKULA. Air is drawn through a vaned rotor and the resulting centrifugal force is employed to separate airborne dust to the peripheral region where it is collected in a hopper. The separation process is studied theoretically and the results used to indicate how model experiments can predict full-scale performance. A horizontal separator with specially shaped guide vanes to improve the efficiency of collection is illustrated.

The fourth paper by Prof. R. ANDRZEJEWSKI deals with the performance of a dust collector which was installed at the Zaziska Gorne Steelworks. The machine was of the circulator type with axial admission of the dusty air and water spray droplets. It was effective for particles smaller than $5\,\mu$ and compared favourably with a cyclone and a venturi scrubber. Simultaneously with its function as dust separator it also served as an exhaust ventilator. Tests are described on effluents from ferro-silicon, ferro-molybdenum, ferro-tungsten and ferro-titanium arc furnaces. A coal dust fired boiler and a marl drying-chamber provided other opportunities for use.

The final paper of the Bulletin, by A. CZAPLICKI, K. GRODZICKI and B. KRAKOWSKA-FULDE, discusses the possibility of recovering germanium and gallium from the flue dust of gas works. The content of these elements varies a great deal with the origin

of the coal consumed. The circulator is a suitable device for separating the dust. Analyses in about 150 gas works were undertaken, other trace elements being evaluated in addition. There is a bibliography of 9 references.

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NEWS

A FILM on the work of the Slough Industrial Health Service has recently been made and is available on loan free of charge, apart from postage. Enquiries should be addressed to the Secretary, Slough Industrial Health Service, Community Centre, Farnham Road, Slough, Bucks.

The film is on 16 mm Kodachrome optical sound-track material and runs for 25 min. It describes all the activities of the Slough Industrial Health Service, including Farnham Park Rehabilitation Centre and the facilities offered by the Occupational Hygiene Laboratories.

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Papers to be published in future issues

K. R. May: A size selective total-aerosol sampler, the tilting pre-impinger.

D. W. Robinson: Variability in the realization of the audiometric zero.

R. J. Sherwood and D. M. S. Greenhalgh: A personal air sampler.

D. E. Hickish and P. J. R. Challen: A study of noise in a circular saw shop and its effect on hearing.

M. Powell and M. A. Lomax: Toxic effects of handling and firing explosives in coal mines.

H. Antweiler: Observations about a histamine liberating substance in cotton dust.

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